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## AN INVESTIGATION OF THE BACKFLOW PHENOMENON IN CENTRIFUGAL SUPERCHARGERS

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# AN INVESTIGATION OF THE BACKFLOW PHENOMENON IN CENTRIFUGAL SUPERCHARGERS

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## SUMMARY

An investigation has been conducted to determine the nature and the extent of the reversal of flow, which occurs at the inlet of centrifugal superchargers over a considerable portion of the operating range. Qualitative studies of this flow reversal were made by lampblack patterns taken on a mixed-flow type impeller, and by tuft studies made on a conventional centrifugal supercharger. Quantitative studies were made on a supercharger specially designed to enable surveys of angularity of flow, static and total pressures, and temperatures to be taken very close to the impeller front face.

The results of this investigation showed that the amount of reversed flow definitely increased as the load coefficient of the supercharger was decreased and that in extreme cases the reversed flow extended several diameters into the inlet pipe. It was found that the chief factor affecting this backflow was the value of the load coefficient at which the supercharger was operating. Evidence was obtained which showed that the backflow was not confined to the clearance space between the impeller blade tips and the impeller front housing but actually extended into the impeller passage. It was also found that the axial velocity near the center of the impeller inlet pipe was practically independent of the operating value of load coefficient. Several effects of backflow on the flow of air at the inlet were observed: a definite increase in inlet-air temperature; a radial temperature gradient at the impeller inlet; a high degree of turbulence; and a definite prerotation, which was particularly large in the outer portion of the impeller inlet annulus.

## INTRODUCTION

It has been generally recognized that, when superchargers are operating at low values of load coefficient, a recirculation of air occurs in the region of the supercharger inlet. This recirculation has frequently been evidenced by a definite temperature rise between the orifice tank and the supercharger-inlet measuring stations, when standard supercharger tests are run at low volume flows. Such abnormal supercharger characteristics as excessively high values of slip factor at low values of load coefficient, surge-free operation at extremely low volume flows, and variations in performance values with varying inlet pressures have all been attributed to recirculation. These assumptions have been based on the fact that the occurrence of recirculation would increase the effective value of load coefficient at which the impeller was operating and alter the velocity distribution at the impeller entrance as well as increase the inlet temperature. Throughout this report the term "backflow" will be used to denote recirculation and is defined as any reverse flow along the impeller front housing or inlet-duct wall.

In order to investigate the nature and the magnitude of the effects of backflow on the flow at the impeller inlet, three series of tests were conducted and are reported herein. The first series of tests was run at the Langley Field laboratory of the NACA on a mixed-flow type impeller to study the development and the extent of backflow with the aid of lampblack patterns. Although these tests definitely showed the existence of a large amount of backflow at low values of load coefficient, they did not show the complete effect of this backflow on the flow distribution at the impeller inlet. Either visual studies or surveys were necessary to obtain additional information of the effects of backflow on the flow at the inlet. The construction of this test unit, however, was such that major alterations would have been required to conduct tests of this type.

A conventional centrifugal supercharger was therefore used in the second series of tests, also run at the Langley laboratory, to determine the nature and the penetration of the backflow in the inlet pipe. For these tests a transparent plastic inlet duct was mounted on the supercharger in place of the inlet elbow and tufts were mounted in this plastic duct to study the flow characteristics in the region of the impeller inlet. Severe backflow was shown to exist at very low values of load coefficient.

These preliminary investigations were purely qualitative and showed only the general trends of backflow. In order to obtain quantitative information of the flow at the entrance to the impeller, it

was necessary to take surveys just in front of the impeller face. A supercharger was specially designed for surveys of this type and consisted of a modified impeller of the type used in the tuft studies, a vaneless diffuser, and a scroll collector. The third series of tests, which was made at the Cleveland laboratory, on this experimental supercharger consisted of surveys of temperature, velocity, and angularity of flow 0.191 inch from the impeller face for various operating conditions.

## APPARATUS

The lampblack studies (series 1) were made on an NACA variable-component test rig (reference 1) using a mixed-flow type impeller in combination with a vaneless diffuser of 20-inch outside diameter. A tube of 1/4-inch outside diameter located 7 diameters upstream from the impeller inlet was used for the injection of lampblack; the tube extended across the inlet pipe of the test rig. Three small holes were drilled in the downstream side of this tube to facilitate the distribution of the lampblack solution, which consisted of 12 grams of lampblack in 4 ounces of SAE 10 oil. For these tests all instruments were removed from the inlet and the outlet pipes with the exception of one outlet total-pressure tube, which was used in adjusting the outlet pressure.

The tuft studies (series 2) were made on a conventional centrifugal supercharger unit which was driven through a 10:1 speed increaser by an aircraft engine. There were 20 diameters of straight pipe between an 8-inch graduated gate valve used as the inlet throttle and the impeller inlet. The last 3 diameters before the impeller were made of transparent plastic to enable visual studies of the flow near the impeller inlet to be made. Wollen tufts were mounted on the walls of this plastic duct as well as on strings across the diameter. The supercharger unit exhausted through an outlet pipe to the atmosphere. No instruments were installed on this rig.

The surveys (series 3) at the impeller entrance were taken on the experimental supercharger (fig. 1) specially designed for work of this type. The impeller was the same type as used in the tuft studies and was modified by reducing the inlet diameter to 6.250 inches and the outlet blade height to 0.437 inch. A vaneless diffuser and a scroll collector, which were so constructed that surveys could be taken very close to the impeller inlet, were used. This supercharger unit was driven by an aircraft engine through a 15:1 speed increaser. (See fig. 2.) This rig was set up and instruments were installed according to the standard specifications

given in reference 2. A Strobotac and a calibrated speed strip were used for speed determination, and a calibrated orifice plate was used for the weight-flow determination.

Surveys of angularity of flow, static pressure, and total pressure at the impeller entrance were made with a 3/16-inch outside diameter Fechheimer tube (fig. 3). Pressure readings were obtained from two holes, which were located $78\frac{1}{2}^{\circ}$ apart and 3/16 inch from the end of the tube. A turntable graduated in degrees was mounted at the top of the Fechheimer tube and was used to measure the angle at which the tube was set. Temperature measurements were obtained from iron-constantan thermocouples by means of a self-balancing potentiometer. Barometric pressure corrected to 32° F was read from a microbarograph.

## METHOD OF TESTS AND CALCULATIONS

The load coefficient $Q/n$ of the supercharger for the lampblack patterns (series 1) was adjusted to the desired value by using the micromanometer reading across the orifice plate and the outlet total-pressure measurement as the indexes. After the unit was run at this condition until complete equilibrium had been obtained, the lampblack solution was injected into the inlet pipe as rapidly as possible. The test unit was then run for an additional 20 minutes to bake the pattern. Before the next run, the pertinent parts of the supercharger unit were thoroughly cleaned so that each succeeding pattern would represent only the conditions for that run. All patterns were made at an impeller tip speed of 1200 feet per second and at values of $Q/n$ varying from the maximum obtainable to that just above violent surge. The inlet-air temperature for all runs was the ambient room temperature. The outlet total pressure was maintained at 10 inches of mercury above atmospheric, except at very high values of $Q/n$, in which case the limited capacity of the outlet system produced such a throttling effect that the minimum outlet total pressure obtainable was well over 10 inches of mercury.

For the tuft studies (series 2) the inlet throttle was first set in the wide-open position and the supercharger was run until equilibrium had been attained. The tufts were then photographed using a photoflood light source and an exposure of approximately 0.1 second. This length of exposure was greater than the period of oscillation of the tufts and gave an indication of the degree of turbulence and also showed the direction of the mean flow. Because

no means of air measurement was provided in these tests, it was impossible to determine the exact value of $Q/n$, but an approximation could be made by comparing the position of the inlet throttle with that of previous calibration tests. Two successive runs were made at values of $Q/n$ that were approximately equally spaced between the maximum value of $Q/n$ and the value of $Q/n$ at surge. The final run was made at a value of $Q/n$ that was just above the surge point.

The backflow surveys (series 3) were made on the experimental supercharger at various values of $Q/n$ and at an outlet pressure of 10 inches of mercury above atmospheric and an impeller tip speed of 1200 feet per second. In addition, surveys were made at impeller tip speeds of 960 and 1080 feet per second.

For each supercharger operating condition surveys of angularity of flow, static and total pressure, and temperature were taken at 1/8-inch intervals on a radial traverse from a boss that was located 0.191 inch upstream from the impeller face on the top of the inlet pipe as shown in figure 4.

The zero angle of the Fechheimer tube was determined by inserting the tube in the inlet pipe until the two holes were approximately halfway between the spinner nut and the inside wall of the inlet duct. The tube was then alined so that a line bisecting the angle between the two holes was parallel with the center line of the inlet pipe. In order to check the zero setting, the assumption was made that at very high values of $Q/n$ the induced rotation of the incoming air was negligible. With the supercharger operating at a very high value of $Q/n$ and the outlet throttle full open, the tube was rotated until the pressures from the two pressure taps were equal. Inasmuch as the angle observed at this condition was $0^{\circ}$, the original zero setting was shown to be correct.

In the pressure and angle surveys with the Fechheimer tube, the tube was adjusted to the proper radius for the point to be taken and then rotated until the pressures from the two pressure taps were equal. Inasmuch as the tube was then pointing directly into the air stream, the angle of flow could be measured. The static pressure of the air stream at that point was also obtained when the pressures from the two pressure taps were equal. In order to obtain total-pressure measurements, the tube was rotated until a maximum absolute pressure was obtained on one of the taps. This maximum pressure was the total pressure at that point. The temperature surveys were made by adjusting an iron-constantan thermocouple to the desired radius and reading the temperature directly from a self-balancing potentiometer.

Before each survey the inlet and outlet throttles were adjusted to give the desired values of $Q/n$ and outlet total pressure. The $Q/n$ value was set using the micromanometer reading across the orifice plate as the index. After the temperatures and operating conditions had become stable, the flow angle, the static pressure, the total pressure, and the temperature surveys were taken at either 1/4-inch or 1/8-inch intervals beginning near the spinner nut and ending close to the wall of the inlet pipe. During the surveys the speed was kept constant and the throttles were left in position. Standard supercharger data were recorded at the beginning of each survey and again at the completion of the survey as a check on the stability of the operating conditions.

The air density was determined from the thermodynamic relation

$$\rho = \frac{p_s}{gRT}$$

where

$\rho$ density, slugs per cubic foot

$g$ ratio of weight to mass

$R$ gas constant for air, 53.5 foot-pounds per pound per $^{\circ}F$

$T$ static temperature, $^{\circ}R$

$p_s$ static pressure, pounds per square foot

The stagnation temperature rise due to compressibility was neglected because the effect of this correction on the density would be small.

Velocity was calculated from the dynamic pressure $q$ by the equation

$$V = \sqrt{\frac{2q}{\rho}}$$

where

$V$ velocity, feet per second

$q$ dynamic pressure, pounds per square foot

Axial and tangential velocity components were calculated by multiplying the cosine and the sine of the angle of flow, respectively, by the total velocity.

## PRECISION

The precision of the angle determinations made with a Fechheimer tube is dependent on the turbulence of the flow, the sensitivity of the pressure-measuring devices, and the zero setting of the tube. The flow encountered in these tests was very turbulent, especially at low values of $Q/n$, and there was a possibility of small errors in balancing the two pressures while making an angle measurement. Consideration of the characteristics of a Fechheimer tube and an examination of the reproducibility of the data indicated that the error in angle measurement induced by these factors is of the order of $\pm 1/2^{\circ}$. Because of the method used in obtaining the zero setting of the tube, however, there may be an error in angle reading of $\pm 1\frac{1}{2}^{\circ}$ but, since the relative values of angle obtained were considered to be of greater importance than the absolute values, this error in zero setting was not important.

The precision of the measurement of static pressure by means of the Fechheimer tube is dependent on the pressure distribution around a cylinder located normal to the direction of air flow. There is, consequently, a possibility of small errors in measurement because the angle at which true free-stream static pressure exists on the surface of the cylinder varies slightly with Reynolds number. This variation is small, however, and the maximum error for the pressure-tap spacing used has been evaluated (see reference 3) as 10 percent of the dynamic pressure. Because the dynamic pressure was taken as the difference between the static and the total pressures, this error in static pressure would result in a maximum error of 5 percent in the velocity determination.

Temperature measurements with the system used are accurate to $\pm 1^{\circ}$.

## RESULTS

### Lampblack Patterns

The adiabatic-efficiency curve at a tip speed of 1200 feet per second for the mixed-flow type supercharger unit on which the lampblack patterns were made is shown in figure 5. The values of Q/n at which these patterns were made are indicated on the curve. Run 1 was made at the maximum value of Q/n obtainable. Runs 2 and 3 were made at Q/n values of 0.225 and 0.220, respectively, because this particular supercharger had a small range of light surge between these values.

Figure 6 is a photograph of the lampblack pattern made on the impeller front housing at a Q/n value of 0.305 (run 1) and shows that there is a limited backflow near the impeller blade tips. Since the air must at all times rotate in the direction of impeller rotation, backflow is evidenced by a reversal of the component of flow that is normal to the tangential component, and backflow is determined from the photographs by a study of the direction of the flow lines.

The pattern made in run 2 at a Q/n of 0.225 (fig. 7) shows that at this operating condition a backflow existed from the impeller blade tips to the impeller inlet but did not extend back into the inlet pipe. Different degrees of backflow occur at four distinct regions. The results of run 3 (fig. 8) also show backflow from the impeller blade tips to the impeller inlet, but the flow lines are continuous. This change in backflow characteristics is probably caused by the change in flow through the supercharger. Although the change in Q/n between these two runs was small, the occurrence of the light surge indicated that a considerable change in flow characteristics through the supercharger must have taken place.

Figures 9 and 10 show the patterns obtained on the impeller front housing and the impeller, respectively, in run 4, which was made at a Q/n value of 0.132. At this operating condition, the backflow starts in the region of the impeller blade tips and extends approximately 6 inches back into the inlet pipe. The pattern obtained on the impeller shows a very light deposit of lampblack near the blade roots. Approximately two-thirds of the distance out from the blade roots there is a heavy lampblack deposit, which is terminated very abruptly. On the outer third of the blades there is a deposit slightly heavier than that near the blade roots. The sharp demarcation between these two regions denotes a cleavage

plane in the flow indicating that air may actually be flowing backwards in the outer portion of the impeller passage. Considerable difficulty was experienced in obtaining the necessary lighting to bring out the desired points without having high lights appear on the photographs. Consequently, the outer third of the blades of the impeller on the left side of figure 10 appears to be nearly free of lampblack deposits because of direct light reflection from this portion of the impeller. The right side of the photograph gives a clearer picture of the true relation of the lampblack deposits.

Photographs of the pattern obtained on the impeller front housing and on the inlet-pipe wall at a $Q/n$ value of 0.100 (run 5) are shown in figures 11 and 12. At this very low value of $Q/n$, the backflow started at the impeller blade tip and extended several diameters up the inlet pipe. The pattern obtained on the impeller in this run was very indistinct due to the high degree of turbulence that existed at the impeller inlet and is not reproduced herein.

This series of lampblack patterns shows that even at maximum $Q/n$ a small amount of backflow exists near the blade tips on the impeller front housing. As the value of $Q/n$ is decreased the extent of this backflow increases until, near the final surge point, the backflow penetrates several diameters into the inlet pipe. There is also indication that this backflow extends into the impeller passage proper and is not confined to the clearance space between the impeller and the impeller front housing. These lampblack patterns gave an indication of the effect of backflow only on the boundary layer and not on the main body of the flow near the impeller inlet.

## Tuft Studies

In the tuft studies made at the inlet of a conventional centrifugal supercharger, the tufts were placed along the inside wall of the duct to obtain information on the penetration and the rotation of the backflow for various values of $Q/n$. Photographs of the attitude of the tufts taken while the supercharger was operated at high, medium, low, and very low values of $Q/n$ are shown in figure 13. At very high values of $Q/n$ (fig. 13(a)) there is no evidence of backflow in the inlet pipe. Figure 13(b), which was obtained for a medium value of $Q/n$, shows that, although the turbulence of the boundary layer has increased, there is still no backflow. Figure 13(c), which is for a low $Q/n$, shows a definite backflow, which extends approximately 1 diameter up the inlet pipe. This backflow is indicated by the change in direction of the tufts

near the impeller inlet. At very low values of $Q/n$ (fig. 13(d)) the backflow is much more severe and extends at least 2 diameters up the inlet pipe.

An indication of the effect on the main body of the flow was obtained by mounting tufts on two strings passed through the center of the duct. Photographs were made of the attitude of these tufts while the supercharger was operated at approximately the same values of $Q/n$ as before. The results (fig. 14) show that, as the value of $Q/n$ is decreased, the turbulence existing near the center of the duct increases continuously. At very low values of $Q/n$ there is a slight indication of prerotation but the random turbulence was so great that no definite trend could be noted.

## Backflow Surveys

In the third series of tests, the three values of $Q/n$ at which surveys were taken are indicated on the adiabatic-efficiency curve (fig. 15). Because it had been previously determined that no backflow existed at the impeller entrance at extremely high values of $Q/n$, the first survey was taken near the point of maximum efficiency, (0.0926 $Q/n$). The second survey was made at the point (0.0824 $Q/n$) where definite evidence of bakcflow was first noted, and the third survey was taken just above the surge point (0.0517 $Q/n$).

The angle of flow, measured by the Fechheimer tube, was the angle between the axial direction and the direction of flow and was measured in a plane normal to the survey. In figure 16 the flow angles $\theta$ obtained from these surveys are plotted against $l/L$, where $l/L$ is the ratio of the radial distance of a particular point from the center line of the inlet pipe to the total radius of the inlet pipe at the survey station. For the $Q/n$ value of 0.0926 the angle $\theta$ is slightly negative. This negative angle indicates a rotation of the incoming air in a direction opposite to that of the impeller and may be caused by an induced rotation from circulation around the impeller blades. At the $Q/n$ value of 0.0824 the angle obtained is negative near the center of the inlet, zero at a radius ratio of 0.62, and then increases rapidly to a positive value of approximately 97° at the duct wall. It is to be noted that for an angle of 90° the axial component of velocity is zero, whereas for values of $\theta$ greater than 90° the axial component of velocity is negative and represents backflow. At the $Q/n$ value of 0.0517 the angle of flow at the inside of the passage is positive and increases to a value of 111° near the duct wall. Backflow is

shown between the radius ratios of 0.84 and 1.00. If the backflow in the supercharger were confined to the clearance space between the impeller and the front housing, this flow would have to expand through an included angle of $68^{\circ}$ to obtain these results at the survey station, which was only 0.191 inch from the impeller face. Inasmuch as the angle of expansion of free jets is in the order of $14^{\circ}$, the backflow must actually extend into the impeller passage. The fact that backflow is not limited to the clearance space is in agreement with the results of run 4 of the lampblack tests. (See fig. 10.) The positive angle near the spinner nut is due to a prerotation caused by the mixing of the backflow, which has a high degree of rotation, with the incoming air. From these surveys it can be seen that at high values of $Q/n$ the flow is nearly axial. As the value of $Q/n$ is decreased, however, the axial component of velocity becomes very small near the wall and a further decrease in $Q/n$ causes a backflow and a relatively high degree of prerotation. The angle of flow represents only the ratio of tangential to axial velocity, and the resultant velocity must also be considered in determining the degree of prerotation and backflow.

A comparison of the axial components of velocity for these surveys is given in figure 17. For a $Q/n$ of 0.0926 the velocity profile is comparatively flat. Decreasing the value of $Q/n$ to 0.0824 causes very little change in the magnitude of the velocity near the center of the inlet. Near the duct wall, however, the velocity is very much lower and an actual reverse flow of air is indicated by the negative values beyond the radius ratio of 0.97. At the $Q/n$ value of 0.0517, the axial velocity near the center of the inlet pipe is the same as in the two previous surveys, but the velocity is much lower in the outer portion of the inlet pipe and backflow is evidenced between the radius ratios of 0.84 and 1.00.

For any impeller tip speed, the angle of attack of the blades is a function of the axial component of velocity and the angularity of the flow. Near the center of the inlet pipe the axial component of velocity and the angularity of the flow are practically independent of the value of $Q/n$ at which the impeller is operating and, therefore, the angle of attack of this portion of the blades is relatively constant regardless of the value of $Q/n$. The angle of attack of the blades in the outer portion of the inlet pipe will vary considerably with $Q/n$ because the axial component of velocity and the angularity of flow change radically with changing values of $Q/n$. For high degrees of prerotation near the outer portion of the blades, however, the angle of attack may decrease.

Figure 18 is a comparison of the tangential components of velocity for these surveys. The velocities are plotted as the ratio of the tangential velocity of the air $V_{tan_a}$ at a given radius to the tangential velocity of the impeller $V_{tan_i}$ at the same radius, thus indicating the variation from a wheel-type rotation. This figure shows that for high values of $Q/n$ the prerotation is negligible. As the value of $Q/n$ is decreased, however, the prerotation near the duct wall approaches the rotational velocity of the impeller, becoming approximately 0.95 of the impeller velocity for a $Q/n$ of 0.0517. Negative values at a $Q/n$ of 0.0926 indicate that the rotation of the air is opposite to the rotation of the impeller.

The results of the temperature surveys, which were taken under the same conditions as the angle and velocity surveys, are presented in figure 19. These curves show the temperature rise between the orifice tank and the survey station plotted against radius ratio at the survey station. Even at the relatively high value of $Q/n$ of 0.0926 where no backflow occurred a definite temperature gradient was observed at the impeller inlet. This increase in temperature near the wall is probably a result of heat transfer from the supercharger housing through the inlet-pipe wall. At the lower values of $Q/n$ the increase in the temperature gradient is due to the presence of backflow and its mixing with the incoming air. Probably some heat transfer always exists at the pipe wall. For this reason the temperature near the wall cannot be used as a measure of the intensity of the backflow. Near the spinner nut, negative values of temperature rise are obtained for the two high values of $Q/n$. Although these negative values are less than the limits of accuracy of the temperature-measuring device, the fact that they occur at both values of $Q/n$ indicates that there is a temperature drop resulting from a velocity increase between the orifice tank and the survey station. At the lowest value of $Q/n$, the positive values of the temperature rise near the inside of the pipe can be due only to backflow. This conclusion is in agreement with the data for the tangential component of the velocity presented in figure 18 and shows that as the $Q/n$ decreases the increase in the amount of backflow results in a mixing action with a consequent increase in temperature and prerotation of the incoming air.

## Effect of Impeller Tip Speed on Backflow

In order to determine the effect of impeller tip speed on the backflow characteristics, surveys similar to those previously presented were made for impeller tip speeds of 960 and 1080 feet per

second. Cross plots of the data thus obtained are presented in figures 20 and 21. Figure 20 shows the variation of the angle of flow with tip speed for several constant values of $Q/n$ and for values of radius ratio of 0.60 and 0.90. Corresponding curves for the effect of tip speed on temperature rise are shown in figure 21. Inasmuch as the variation shown does not follow a definite trend, no appreciable effect of tip speed on the characteristics of backflow is indicated in the range of tip speeds tested.

## DISCUSSION

Because all flow must be instigated by a pressure gradient, the occurrence of backflow must be the result of a pressure gradient exceeding that which can be overcome by the momentum of the forward flow. It should be noted that at all times there will be an adverse pressure gradient from the impeller entrance to the blade tips. This gradient will act on the relatively slow moving air in the clearance space and tend to cause a backflow within the clearance space. Although this tendency may have an appreciable effect on the backflow, it does not account for the reverse flow of air from the impeller passages.

In order to determine the pressure gradient along the flow path near the impeller front housing, the summation of the components of three pressure gradients must be considered. These pressure gradients are the result of centrifugal force, curvature of the impeller front housing, and changes in flow area of the impeller passages. Although, in the case of an ideal fluid, the centrifugal force would have no effect on the velocities, the compressible and viscous properties of air render it necessary to consider the effects of this force.

The principal components of the pressure gradients resulting from centrifugal force can be divided into two parts: (1) those resulting from an increase in the radius of rotation of the air, which are independent of any changes in the relative velocity of the flow for equilibrium and, except for the increase in the density of the air with the pressure may be disregarded in this discussion; (2) those resulting from an increase in the angular velocity of the air, which are dependent upon a change in relative velocity of the air with respect to the impeller. The pressure gradient must be held in equilibrium by the reduction of the relative tangential component of the velocity of the air. This component of velocity will be just sufficient to maintain equilibrium, and any losses that occur must be at the expense of the momentum

of the axial component of velocity. In the conventional-type impeller, this pressure gradient resulting from rotational acceleration will be confined to a region near the impeller inlet and will increase in magnitude with decreasing values of $Q/n$.

The second pressure gradient to be considered is caused by the curvature of the flow path. In the region where the convex curvature is increasing, this pressure gradient will be favorable, whereas in the region where the curvature is decreasing, this pressure gradient will be adverse.

The third consideration is the rate of change of the effective flow area. If this flow area does not decrease rapidly enough as the density increases, the product of the density and the flow area $\rho A$ will increase and the velocity must decrease to maintain continuity. This reduction of velocity will create an adverse pressure gradient along the flow path.

Because these three factors are complexly interrelated, no mathematical solutions can be found for determining the magnitude of the resultant pressure near the impeller front housing. The problem is further complicated by the difficulty encountered in determining the true flow path and flow area throughout the impeller. From a study of the extreme cases of very high and very low values of $Q/n$, however, it is possible to predict the trend of the expected backflow.

For conventional-type impellers operating at high values of $Q/n$, the rotational acceleration will cause a continually increasing pressure gradient near the inlet. On the other hand, the increasing curvature of the front housing will produce a pressure gradient that will oppose the gradient caused by rotational acceleration. A consideration of the flow area indicates that it will not contribute to the production of a favorable pressure gradient. It appears likely that at high values of $Q/n$ the momentum of the tangential component of relative velocity will be sufficient to overcome any resulting adverse pressure gradient and, if it is not, the added momentum of the axial component of velocity may contribute to the inhibition of backflow in the region of the impeller inlet.

A consideration of the flow near the impeller tip at high values of $Q/n$ shows that an adverse pressure gradient may exist due to decreasing curvature of the front housing. Furthermore, the increasing density in this region together with a practically constant flow

area causes a considerable adverse pressure gradient in addition to that created by the centrifugal force. This additional gradient must be balanced by the momentum of the air and, if this momentum is insufficient, a backflow will occur in the region of the blade tips.

At low values of $Q/n$, if the incoming flow is purely axial, the rate of the rotational acceleration near the impeller inlet will tend to be much greater than for high values of $Q/n$ because of the higher angle of attack of the blades with respect to the air and the resulting higher blade loading at the leading edges of the blades. As a result a much more severe adverse pressure gradient will be developed because the rate of rotational acceleration in a given axial distance will be increased. In addition, the opposing effect due to increasing curvature will be less and the effect of area will still be adverse. Furthermore, the momentum resulting from the axial component of velocity will be much smaller for low than for high values of $Q/n$. These factors indicate that the tendency toward backflow in the region of the impeller inlet will be much greater for low than for high values of $Q/n$; this trend is in agreement with the test results obtained. At low values of $Q/n$ the effects of the decreasing curvature of the front housing and the increasing density in the region of the blade tips will be approximately the same as for high values of $Q/n$. The magnitude of the backflow, however, is greater due to the reduced momentum of the incoming air. This conclusion is in agreement with the test results, since backflow in the region of the blade tips was obtained at all values of $Q/n$.

At a zero value of $Q/n$ the centrifugal pressure gradient would cause the pressure near the hub of the impeller inlet to be less than that in the inlet pipe, whereas that near the tip of the blades would be greater than that in the inlet pipe. This pressure distribution causes a circulating flow, which enters the impeller near the hub and is discharged into the inlet pipe from the outer portions of the impeller annulus. The axial velocity distribution observed at low values of $Q/n$ may be regarded as an extension of this trend.

## SUMMARY OF RESULTS

From tests made on superchargers with axial inlets the following results were obtained. The addition of a supercharger inlet elbow and carburetor to the system will definitely alter the flow

characteristics at the impeller entrance. Caution must therefore be exercised in applying the results of these tests to actual supercharger installations.

1. At high values of load coefficient, any backflow that may exist is confined to a region near the impeller blade tips. As the value of load coefficient is decreased, however, this region of backflow extends backward along the impeller front housing until, at very low values of load coefficient, the backflow penetrates several diameters into the inlet pipe.

2. The value of load coefficient is the determining factor of the backflow characteristics; the effect of impeller tip speed is negligible.

3. At very low values of load coefficient, the backflow actually extends into the impeller passage and is not confined to the clearance space between the impeller blades and the impeller front housing.

4. The axial component of velocity near the center of the impeller inlet pipe does not appreciably change with load coefficient.

5. The mixing of the heated backflow air causes a definite increase in the inlet-air temperature and a very large radial temperature gradient at the impeller inlet annulus.

6. The backflow results in a high degree of turbulence and a definite prerotation in the inlet pipe at the impeller entrance. Although the degree of prerotation near the center of the pipe is not appreciable, that near the inlet-duct wall has approximately the same magnitude as the impeller rotation.

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2. NACA Special Subcommittee on Supercharger Compressors: Standard Procedures for Rating and Testing Centrifugal Superchargers. NACA ARR, Feb. 1942.

3. Fechheimer, Carl J.: Measurement of Static Pressure. Mech. Eng., vol. 49, no. 8, Aug. 1927, pp. 871-873; discussion, pp. 873-874.

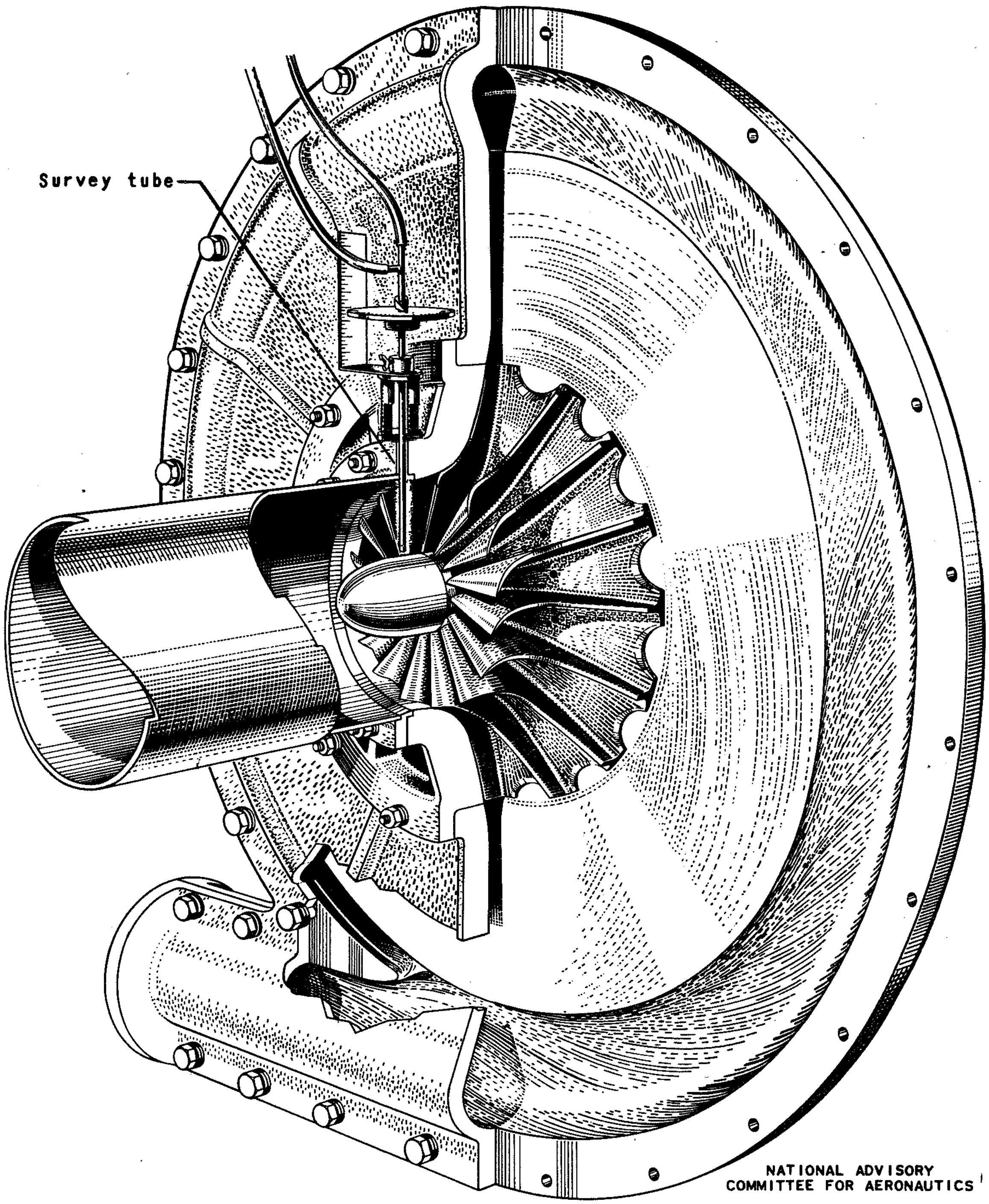


Figure 1. - Experimental supercharger test unit.

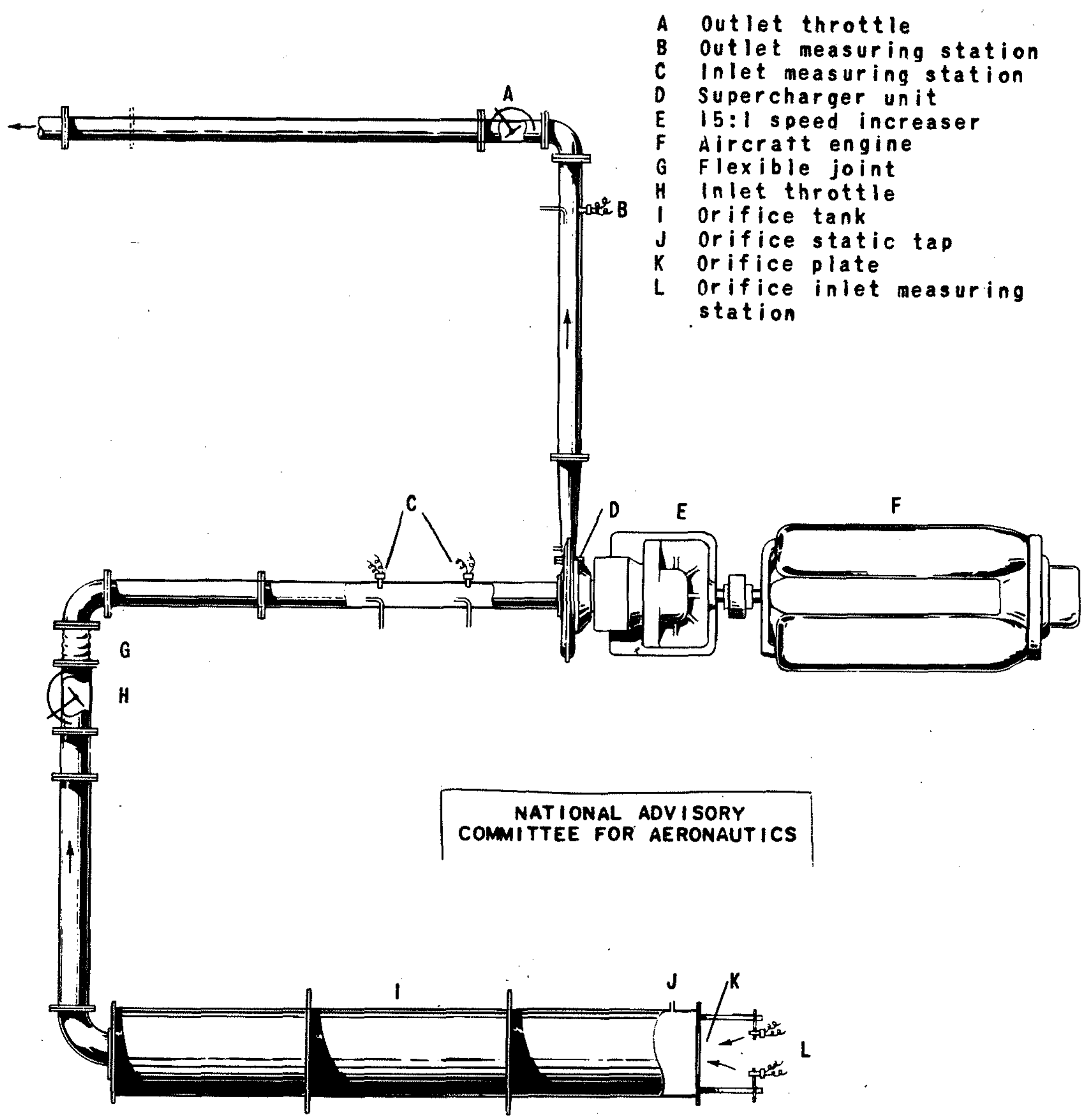


Figure 2. - Schematic diagram of experimental supercharger test unit.

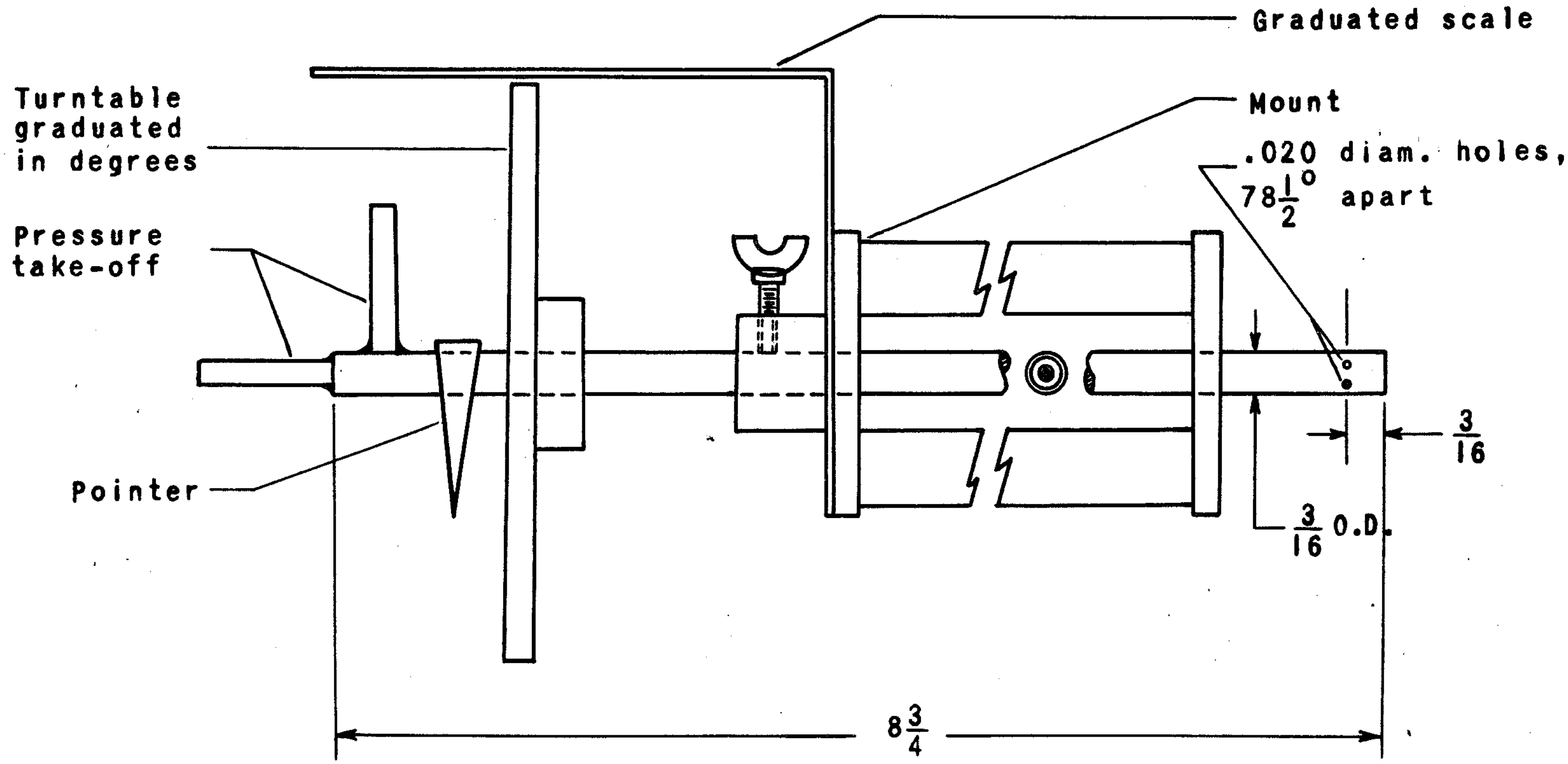


Figure 3. - Fechheimer survey-tube assembly. All dimensions in inches.

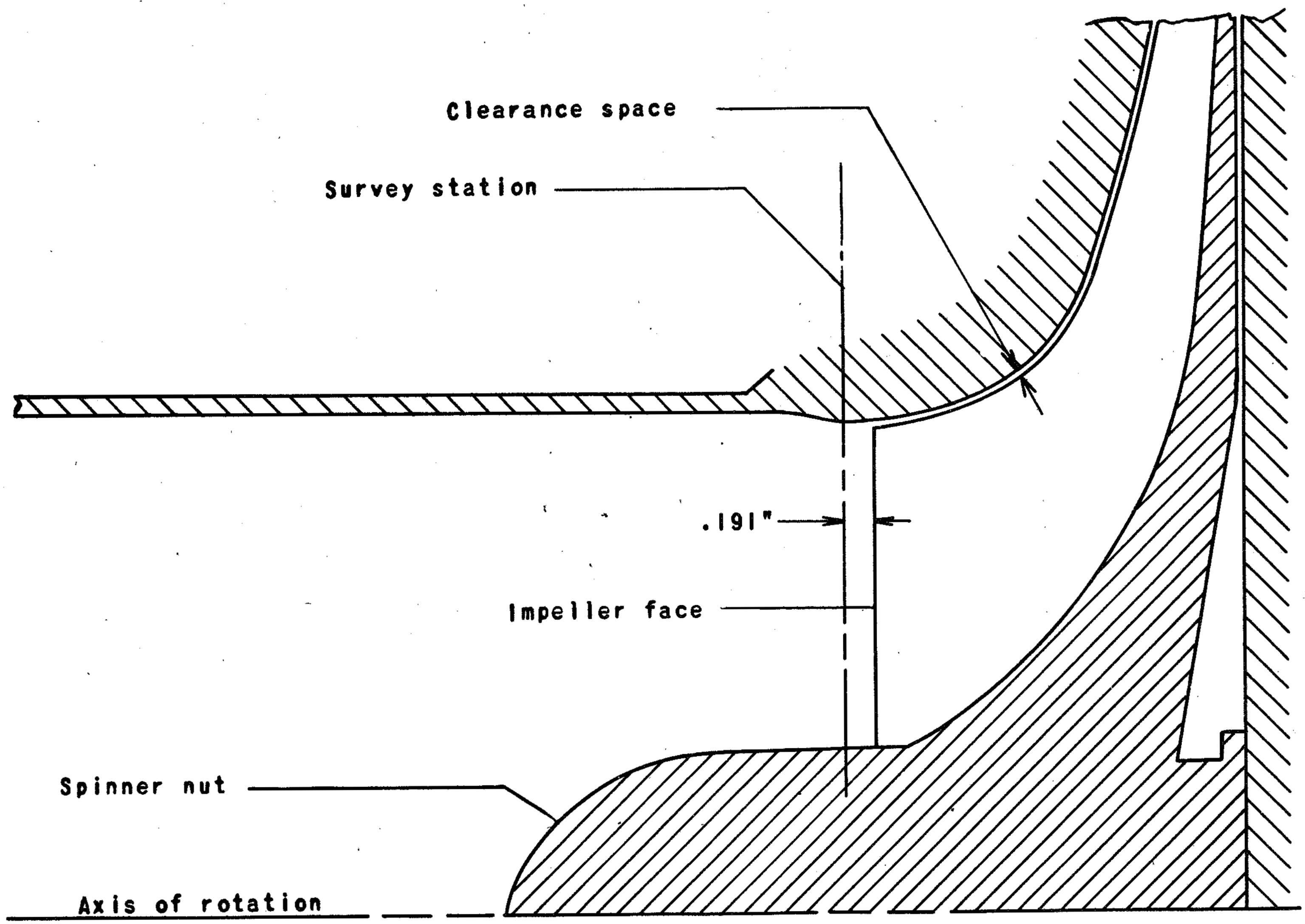


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Figure 4. - Location of survey station with respect to impeller.

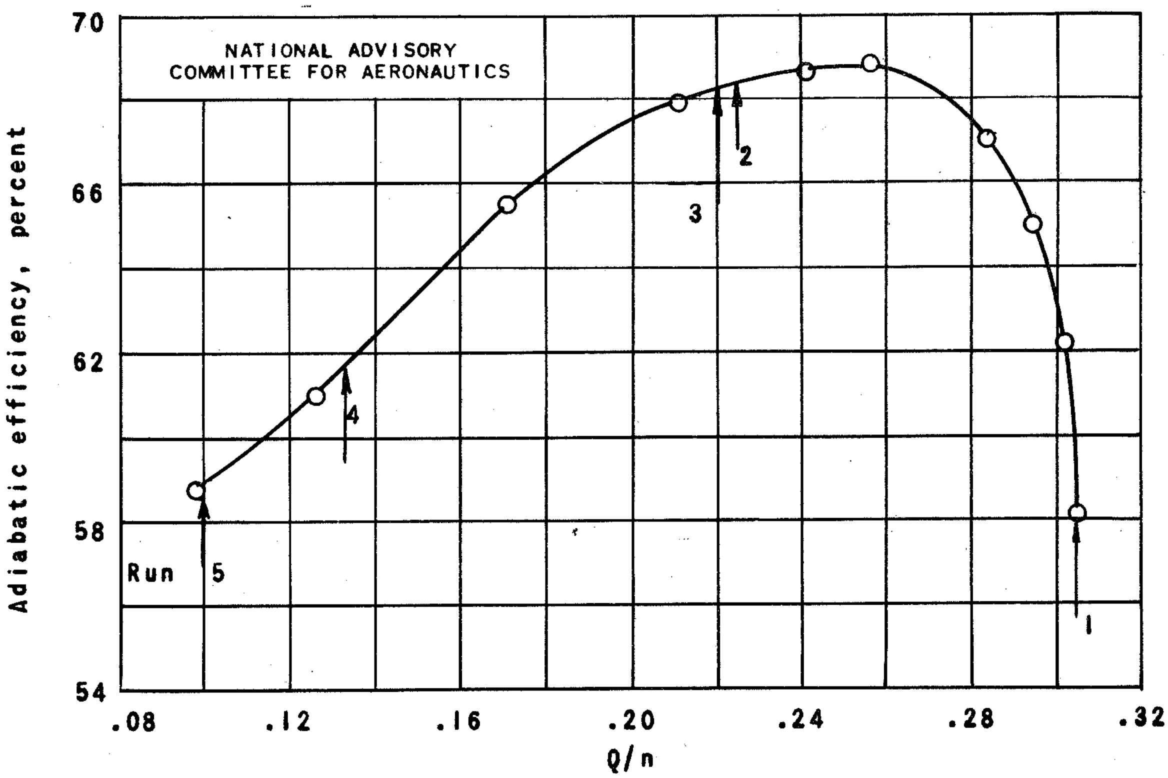



Figure 5. - Adiabatic efficiency of mixed-flow type supercharger unit for an impeller tip speed of 1200 feet per second and an outlet pressure of 10 inches of mercury above atmospheric.

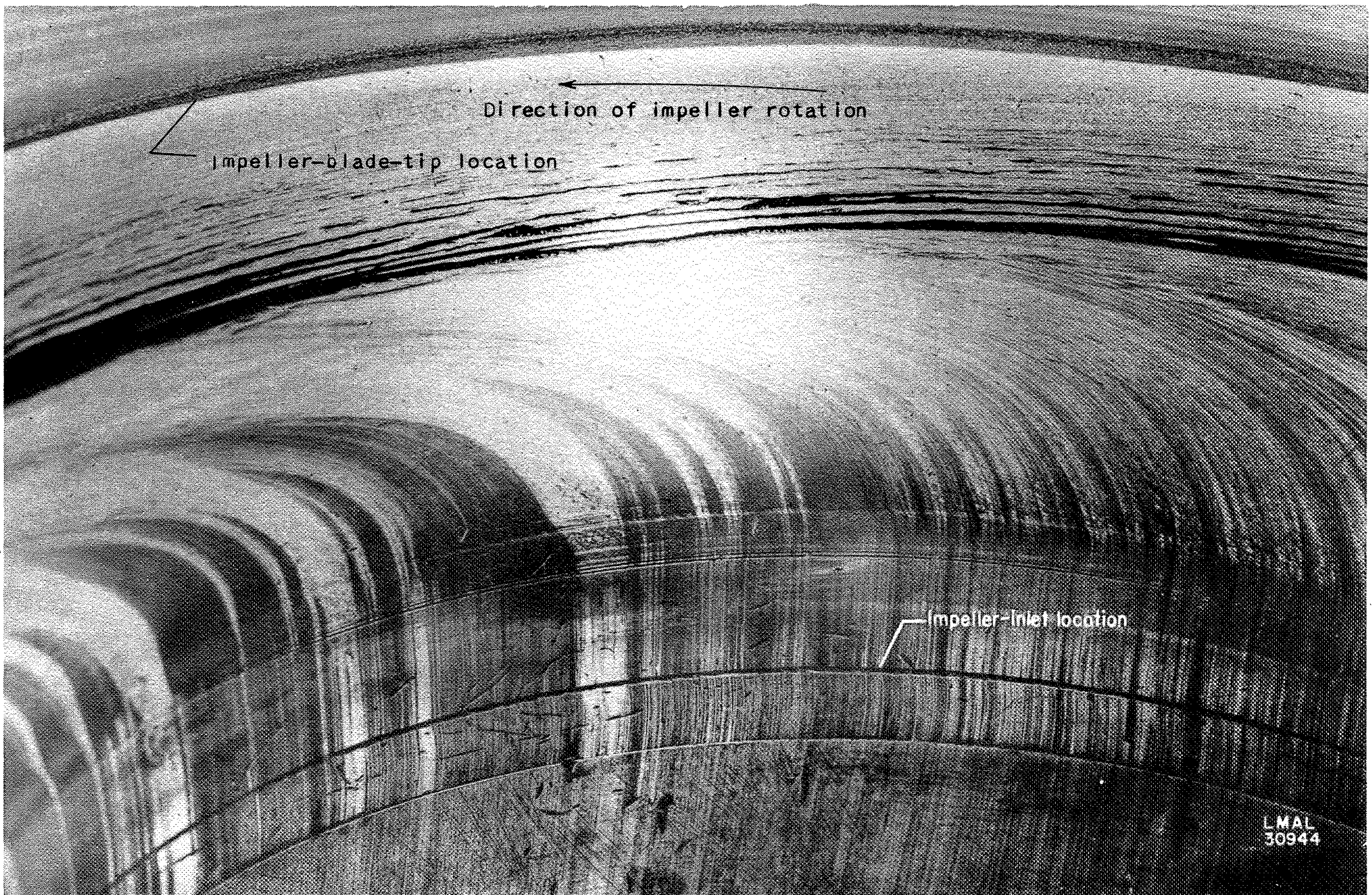



Figure 6. - Lampblack pattern on mixed-flow type impeller front housing for a Q/n of 0.305, run I.

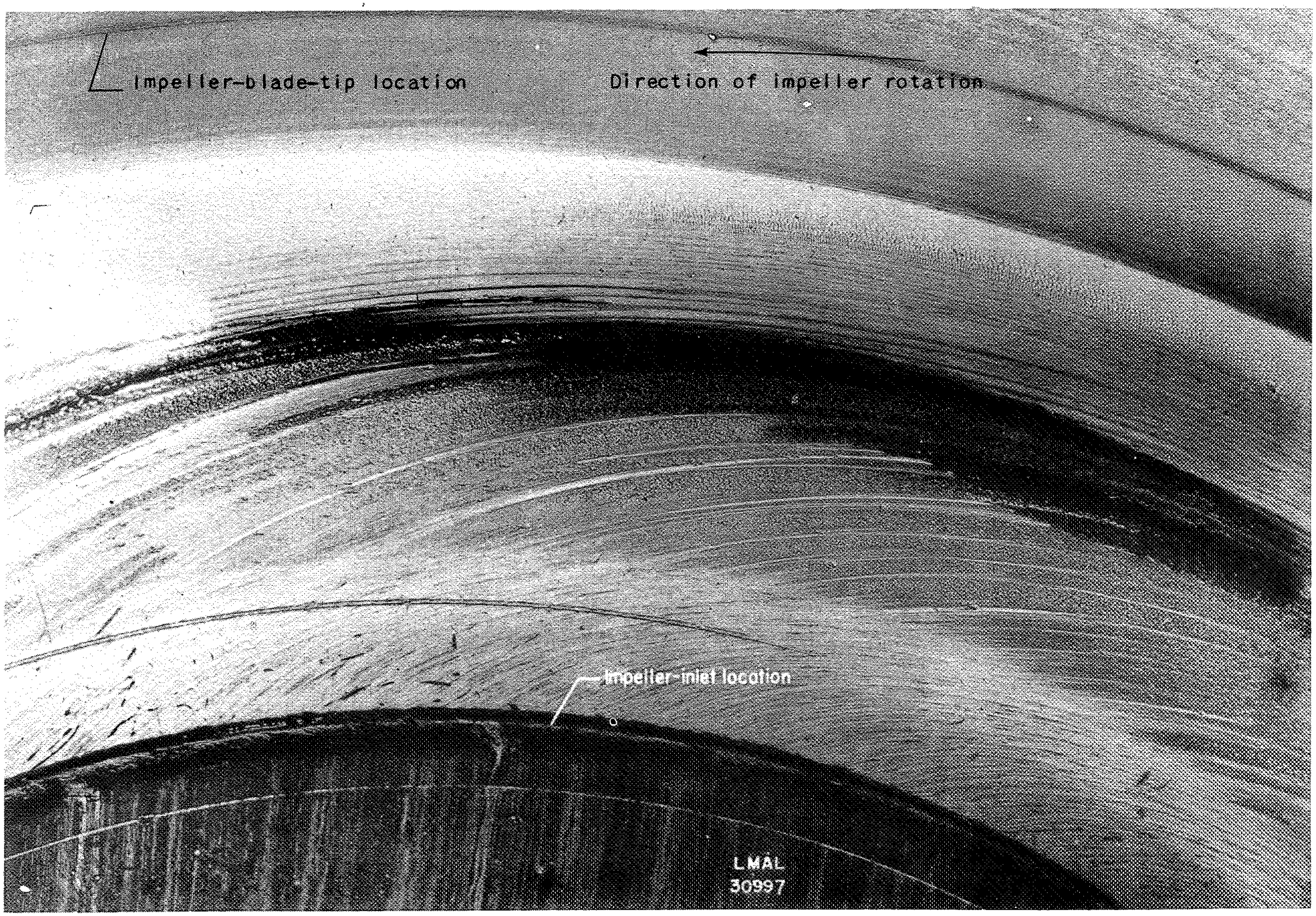



Figure 7. - Lampblack pattern on mixed-flow type impeller front housing for a Q/n of 0.225, run 2.

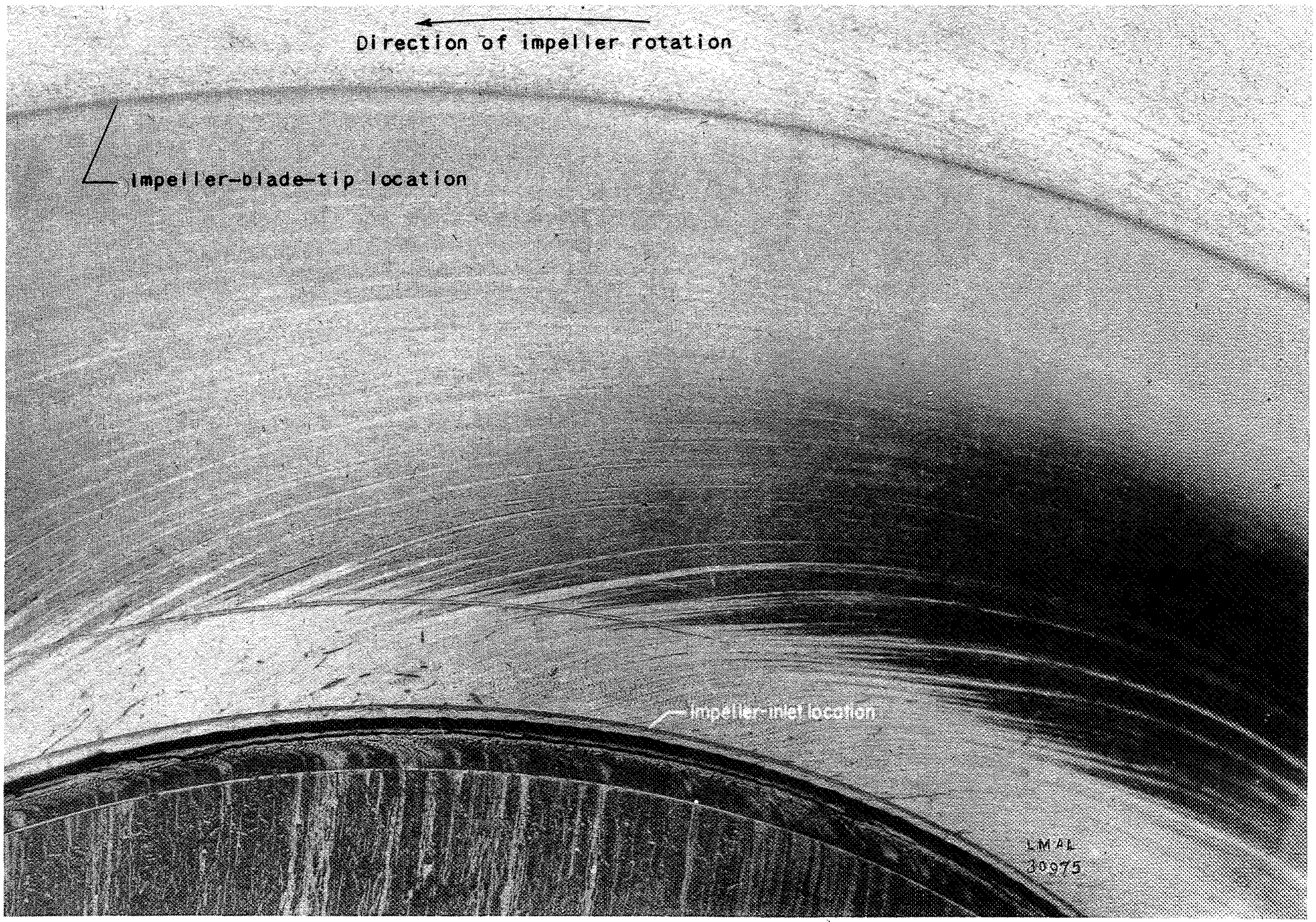



Figure 8. - Lampblack pattern on mixed-flow type impeller front housing for a Q/n of 0.220, run 3.

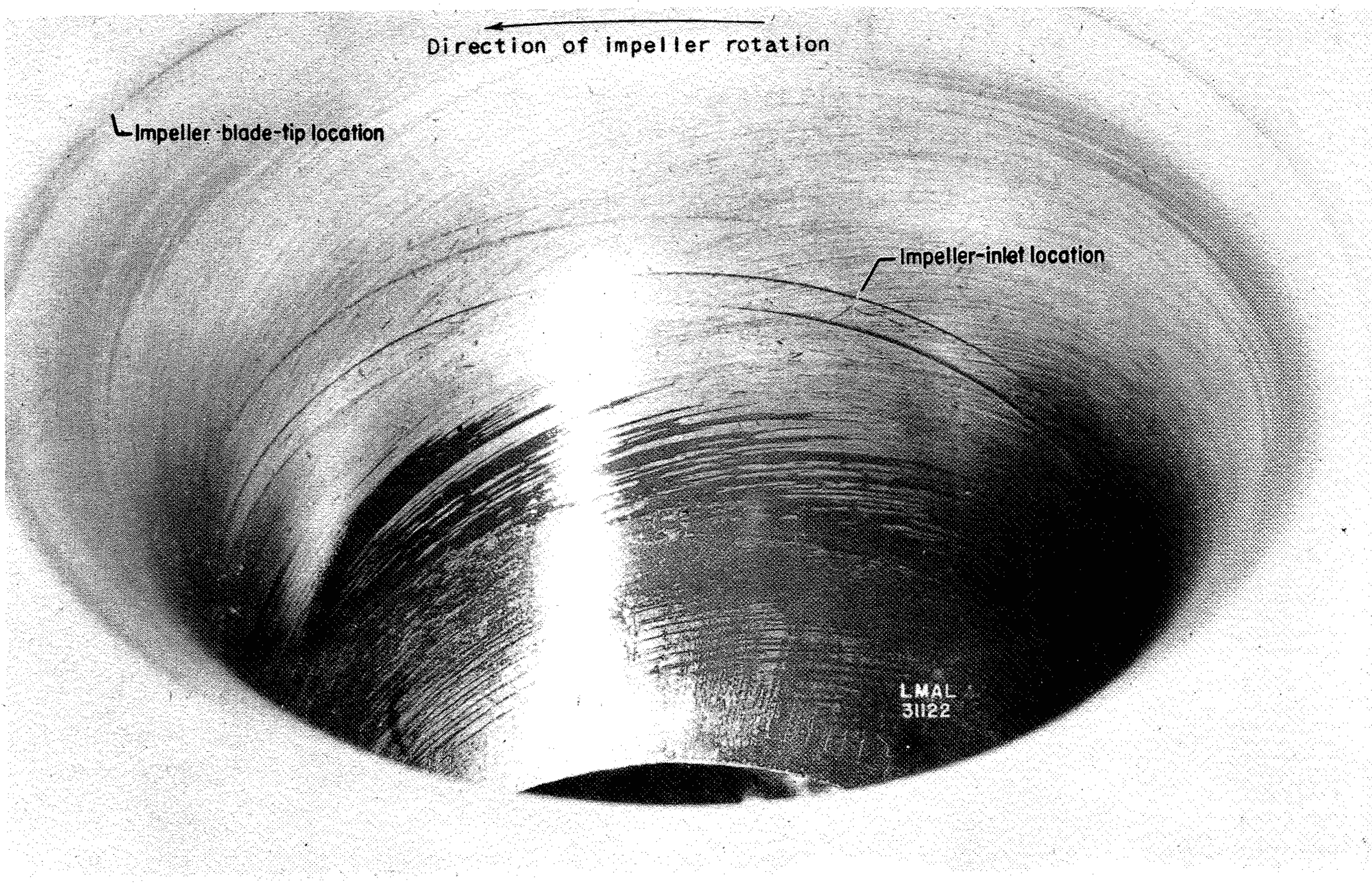



Figure 9. - Lampblack pattern on mixed-flow type impeller front housing for a Q/n of 0.132, run 4.

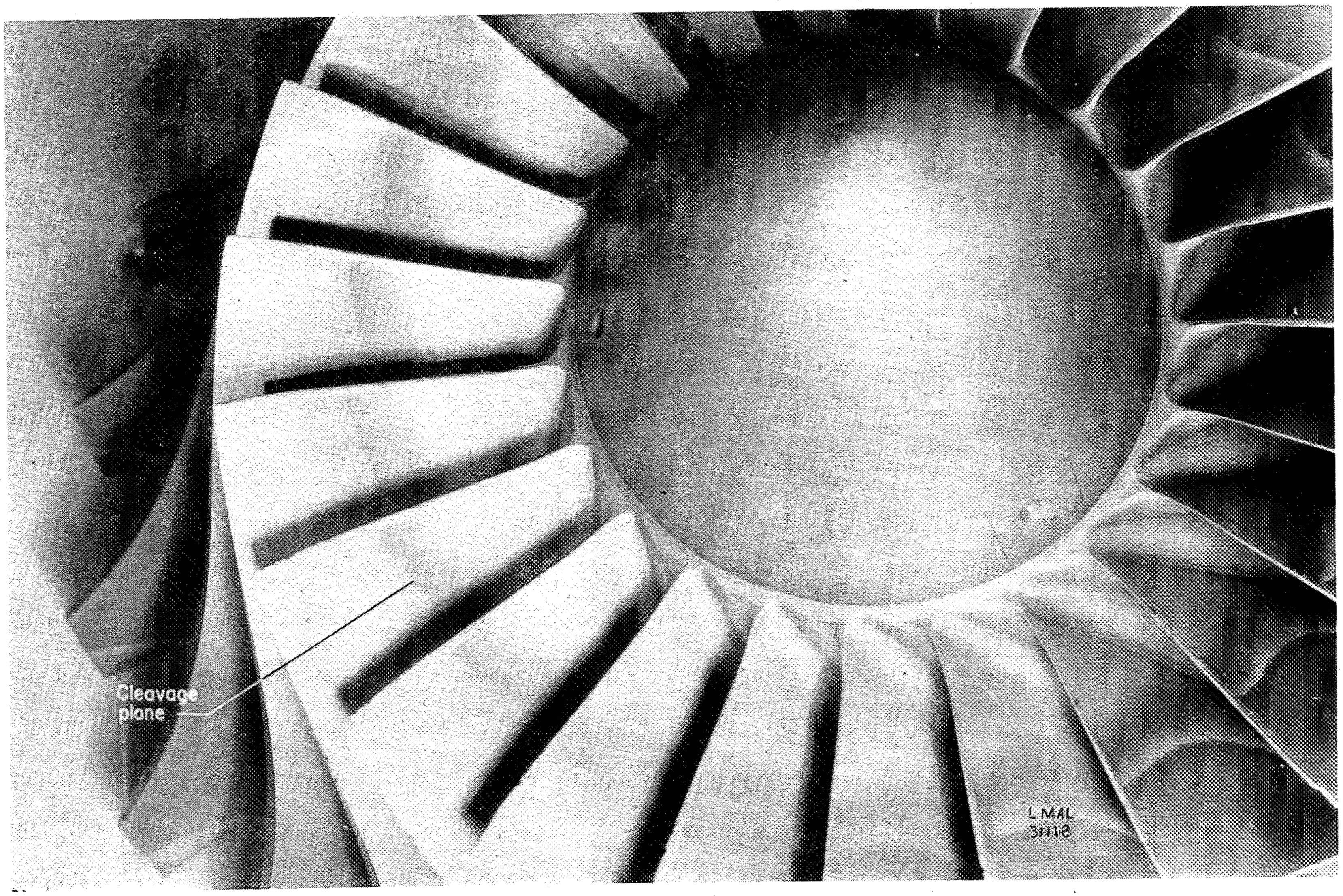



Figure 10. - Lampblack pattern on mixed-flow type impeller for a Q/n of 0.132, run 4.

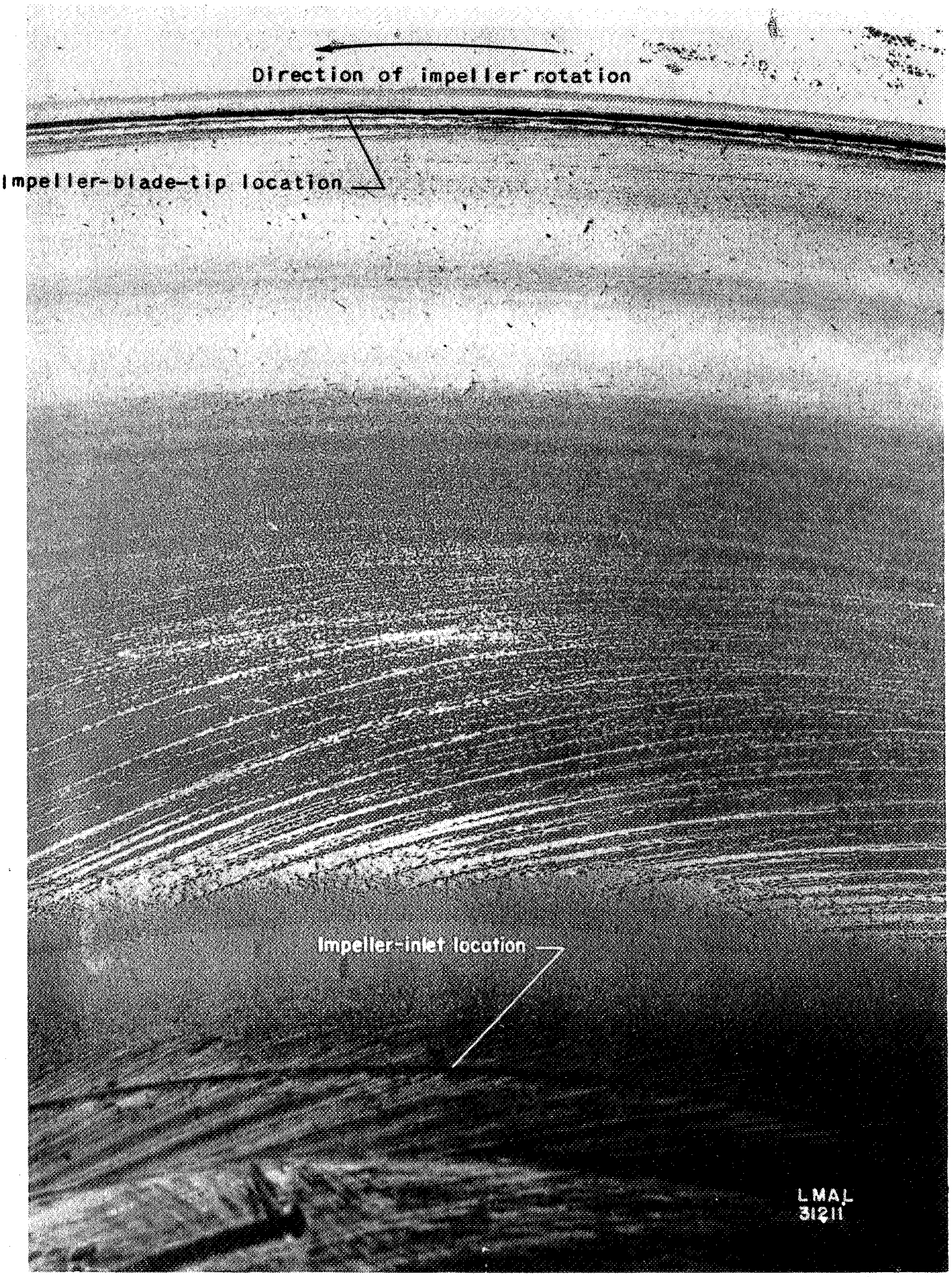



Figure 11. - Lampblack pattern on mixed-flow type impeller front housing for a Q/n of 0.100, run 5.

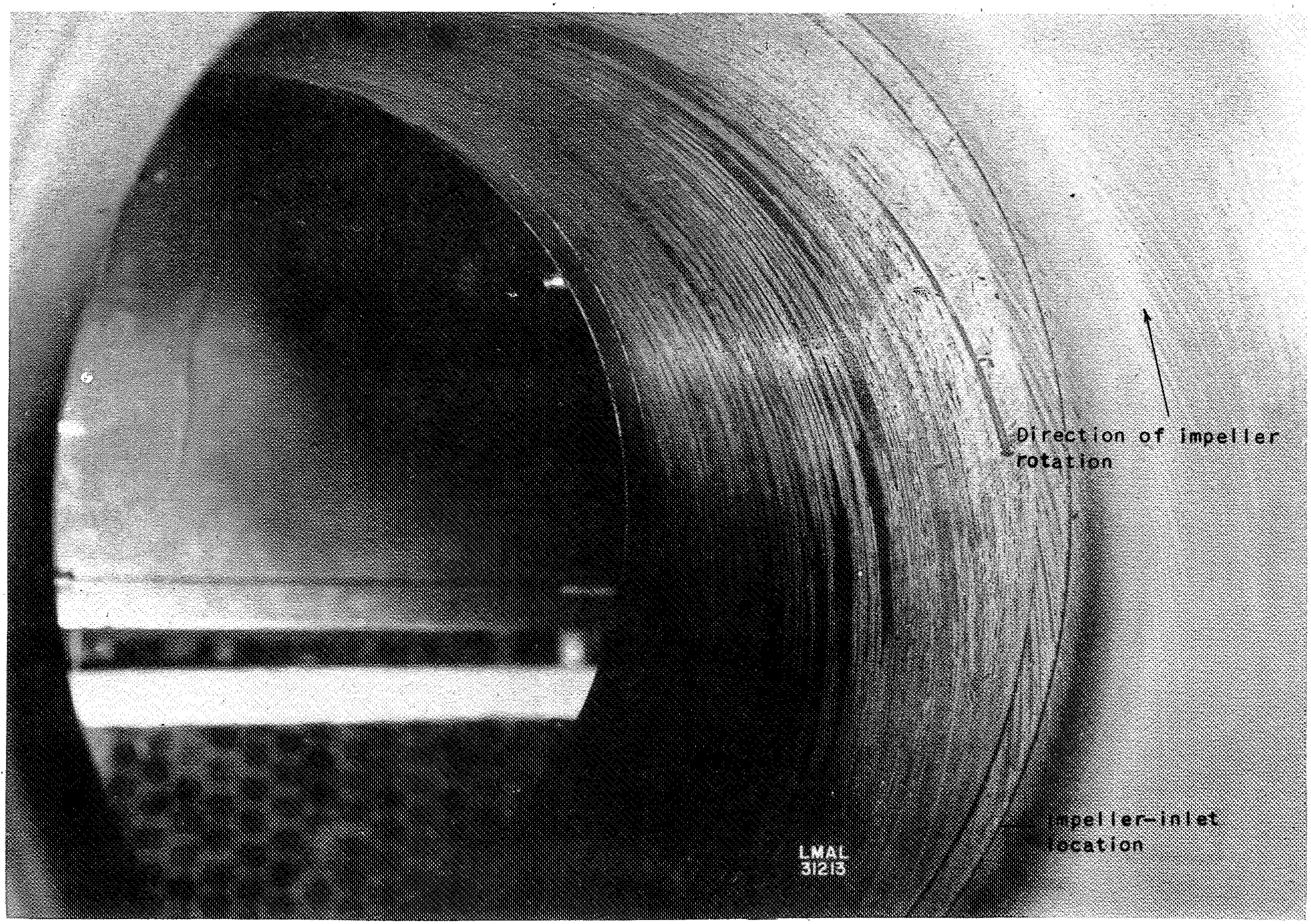
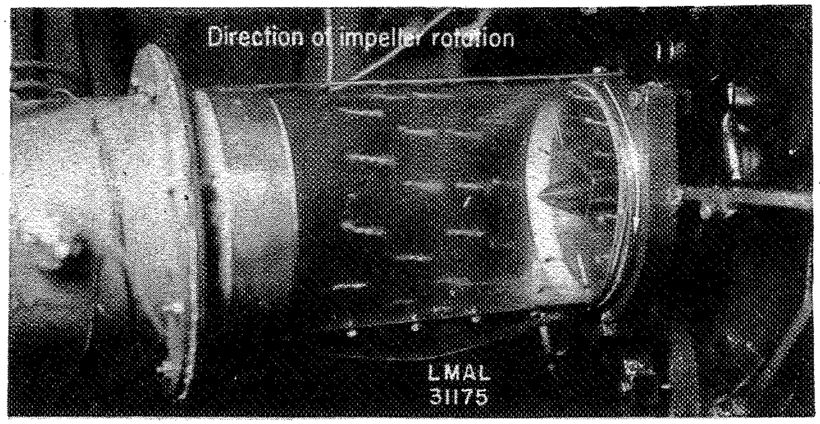
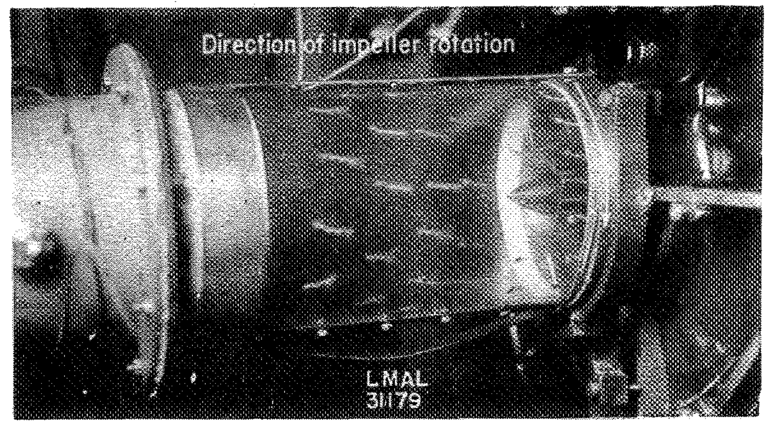




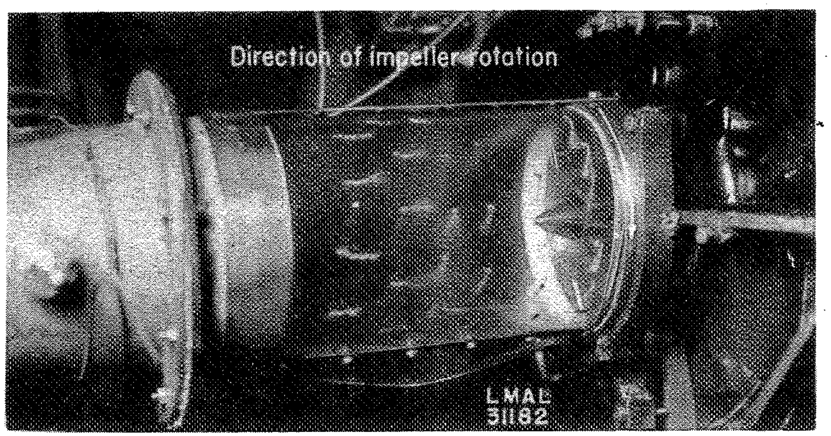

Figure 12. - Lampblack pattern on mixed-flow type supercharger unit inlet pipe for a Q/n of 0.100, run 5.



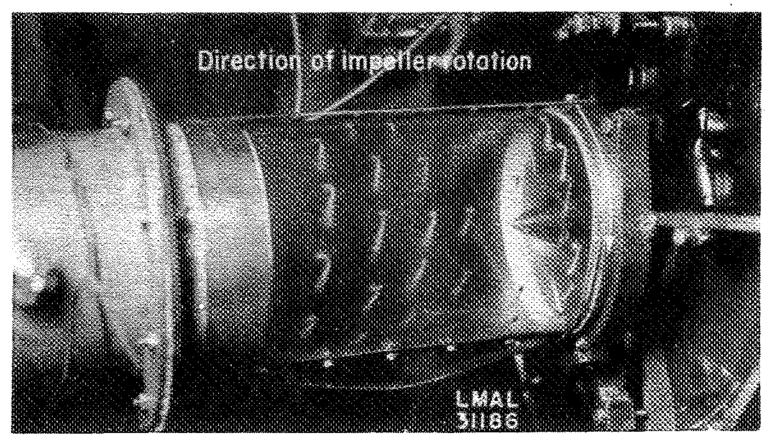

(a) High Q/n.




(b) Medium Q/n.

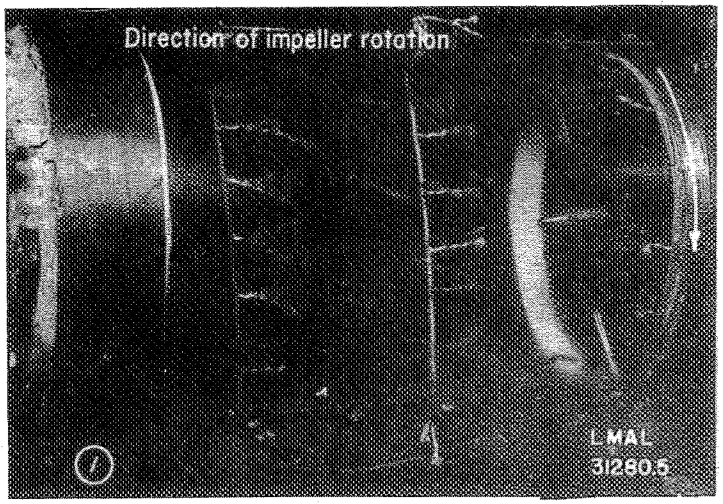



(c) Low Q/n.

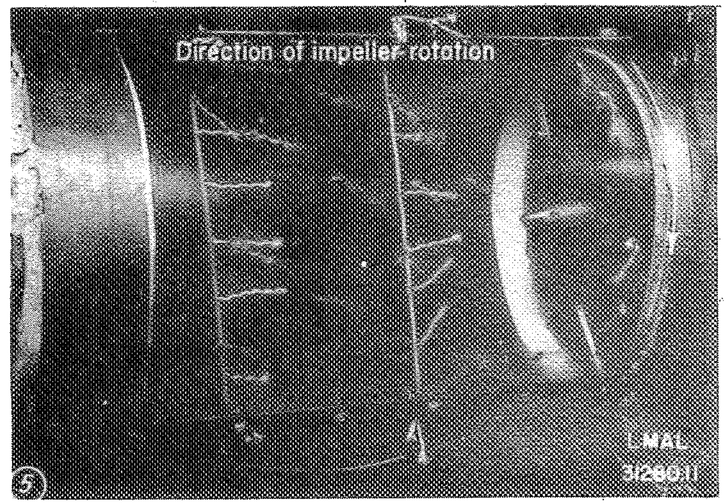



(d) Very low Q/n.

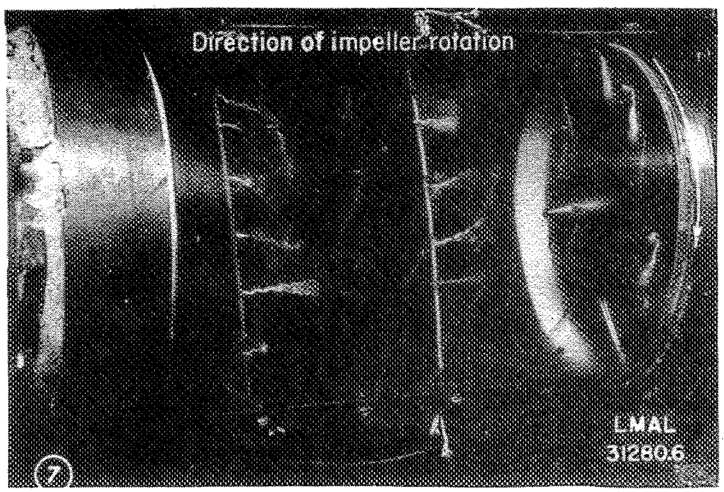
Figure 13. - Tuft studies of boundary-layer flow in the inlet pipe of a conventional centrifugal supercharger.



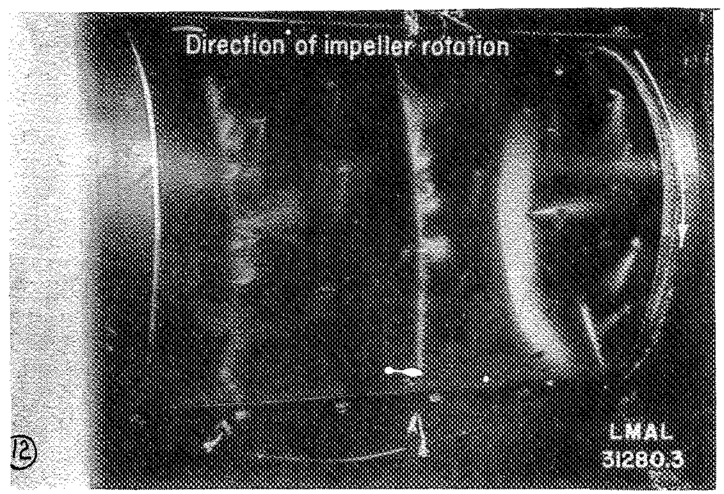

(a) High Q/n.




(b) Medium Q/n.




(c) Low Q/n.




(d) Very low Q/n.

Figure 14. - Tuft studies of the main flow in the inlet pipe of a conventional centrifugal supercharger.

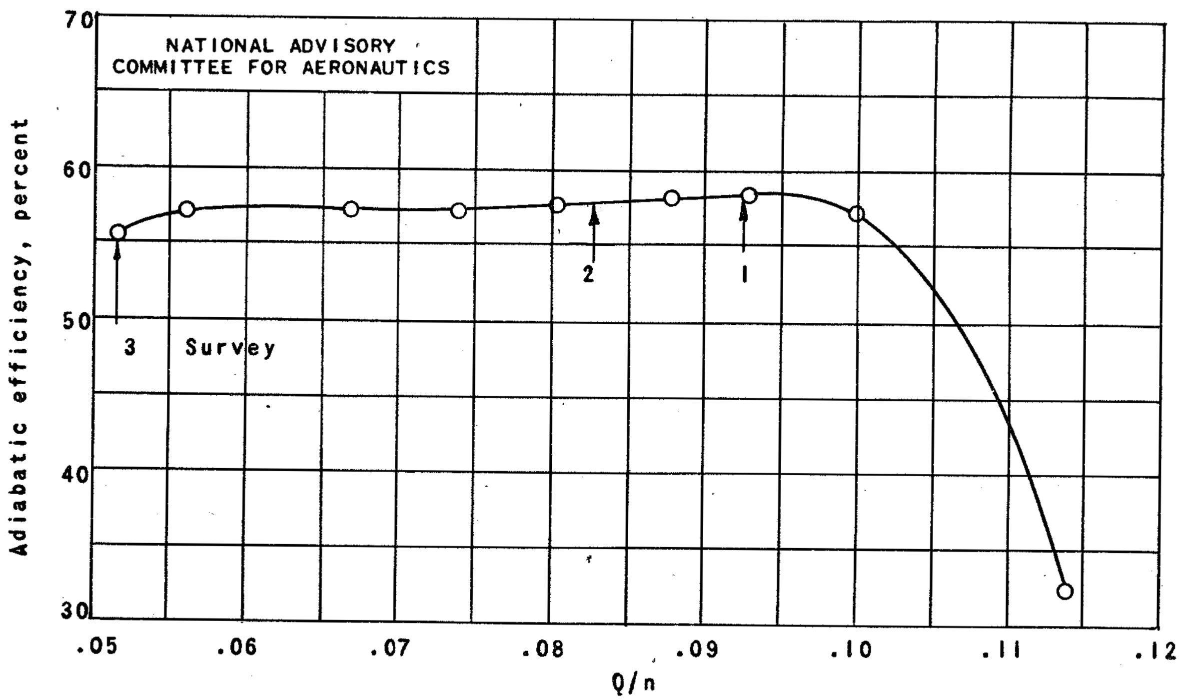



Figure 15. - Adiabatic efficiency of the experimental supercharger for an impeller tip speed of 1200 feet per second and an outlet pressure of 10 inches of mercury above atmospheric.

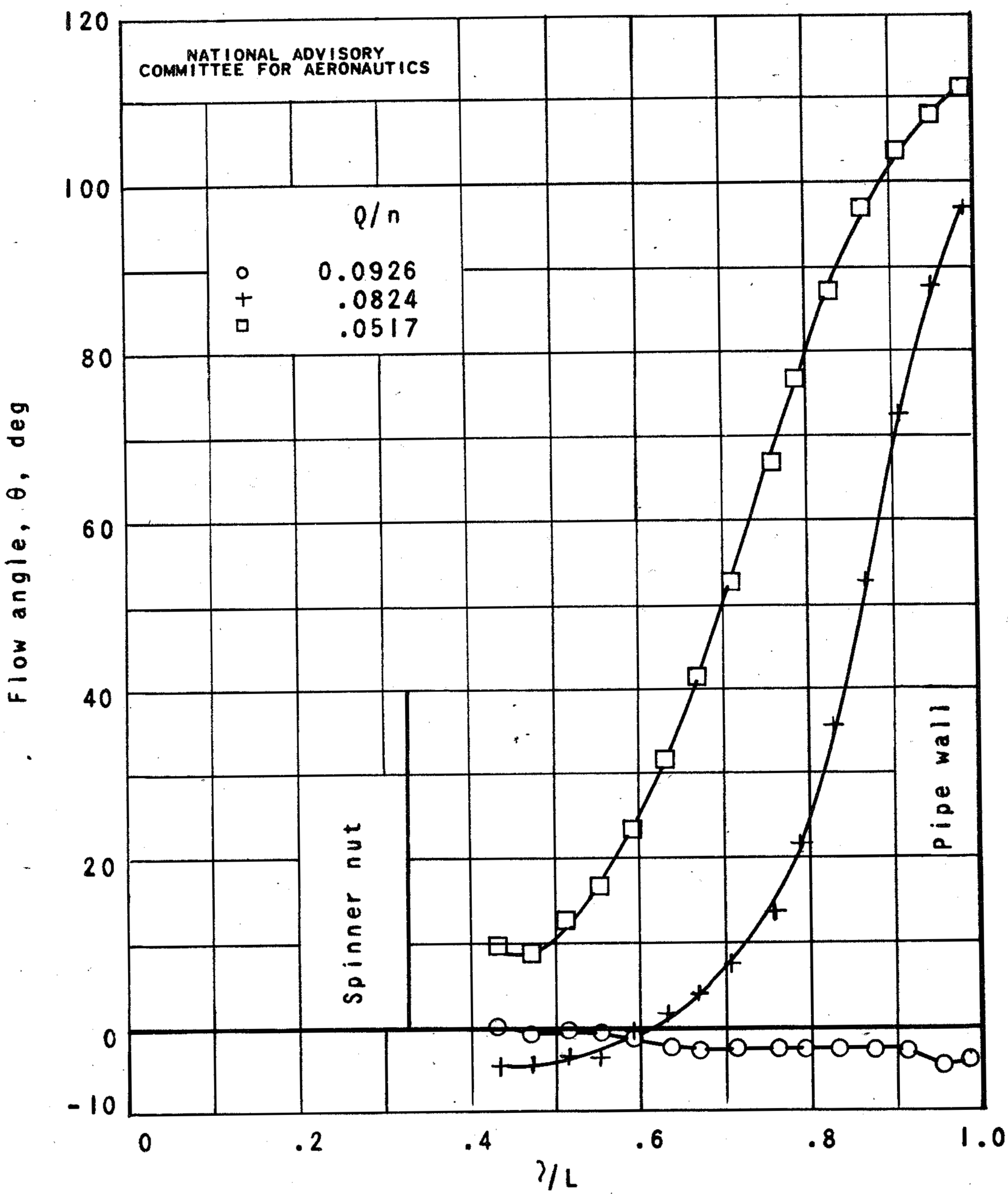



Figure 16. - The effect of various values of Q/n on the angularity of flow at the inlet of the experimental supercharger for an impeller tip speed of 1200 feet per second and an outlet pressure of 10 inches of mercury above atmospheric.

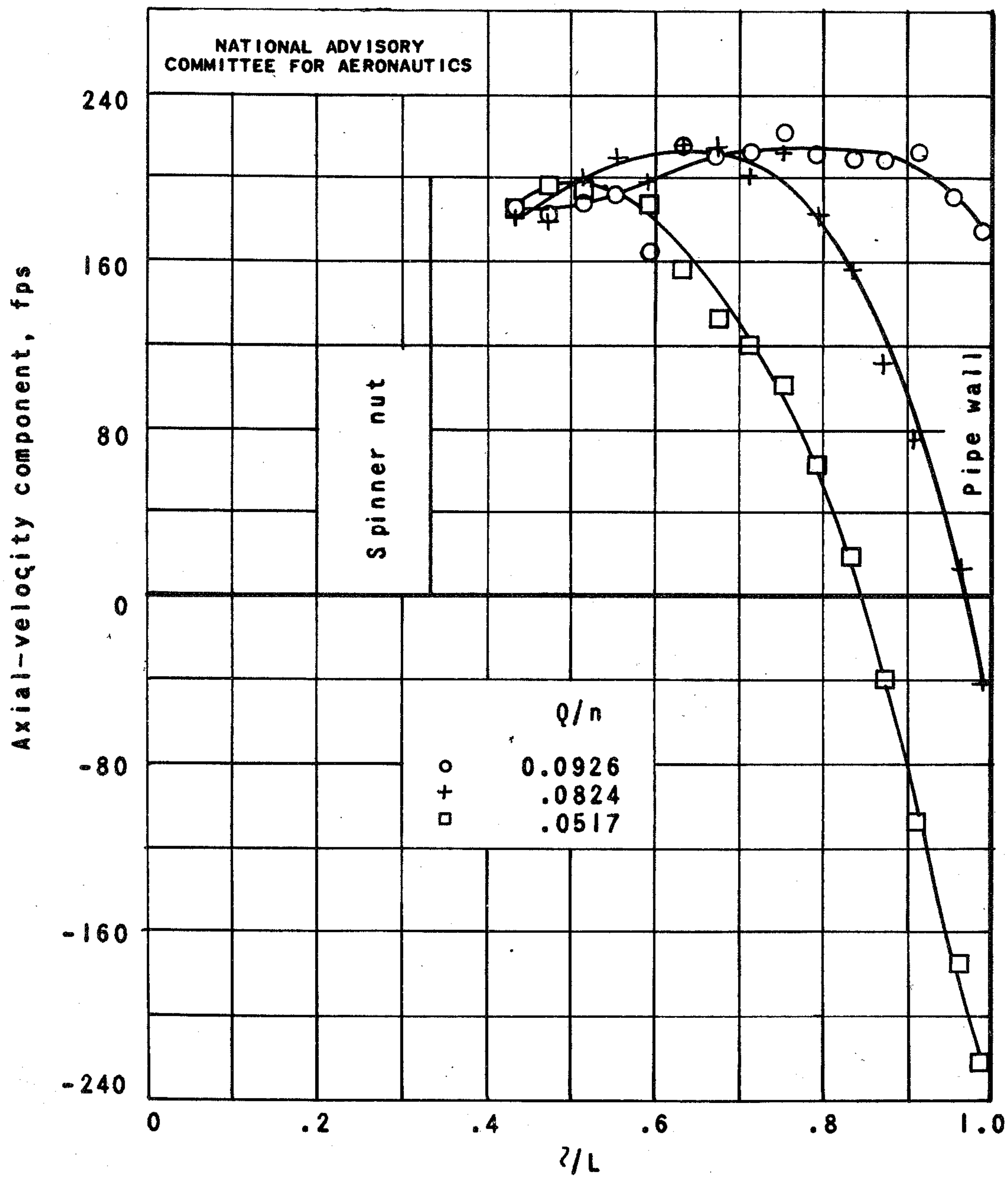



Figure 17. - The effect of various values of Q/n on the axial-velocity components at the inlet of the experimental supercharger for an impeller tip speed of 1200 feet per second and an outlet pressure of 10 inches of mercury above atmospheric.

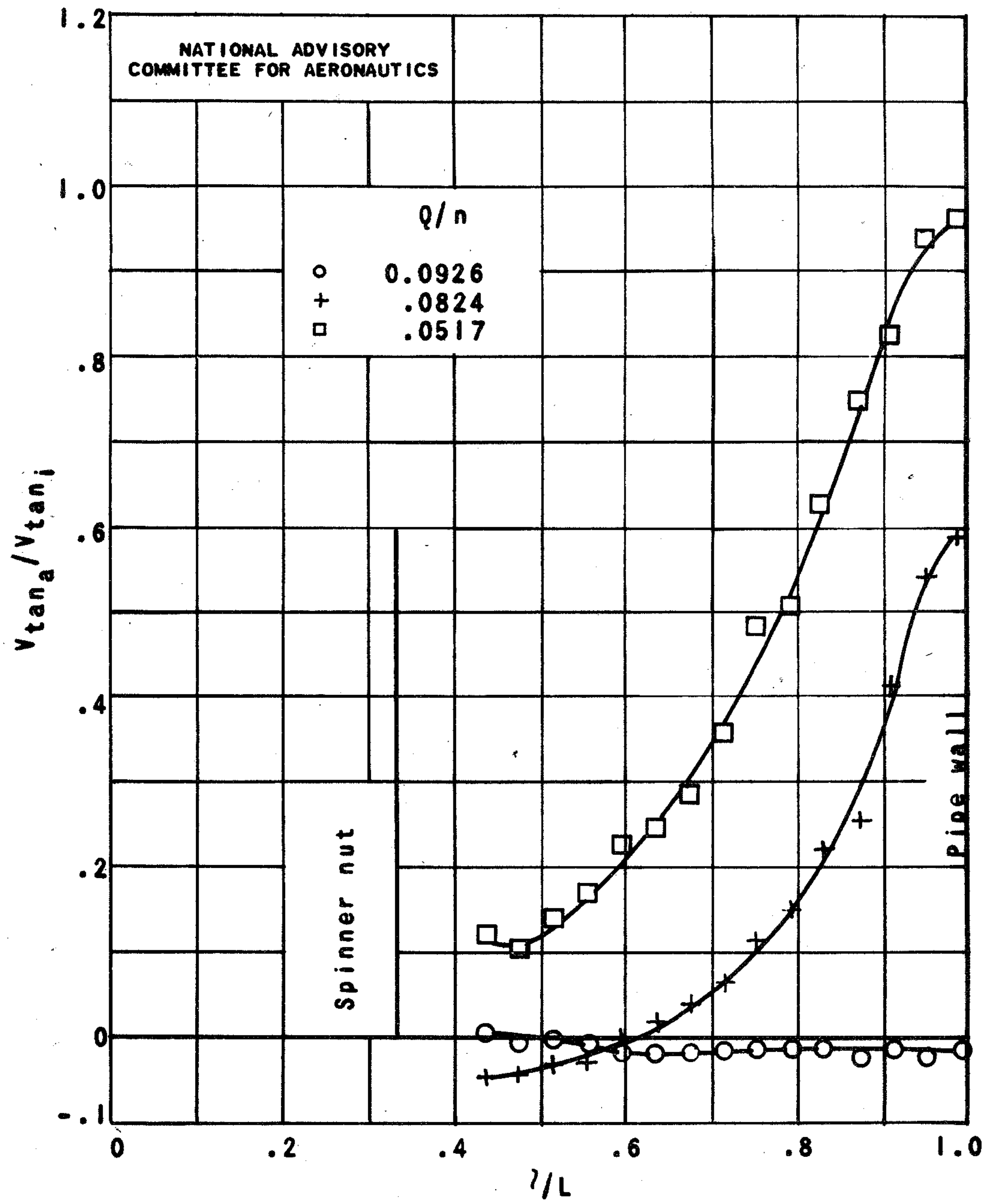



Figure 18. - The effect of various values of Q/n on the tangential-velocity components at the inlet of the experimental supercharger for an impeller tip speed of 1200 feet per second and an outlet pressure of 10 inches of mercury above atmospheric.

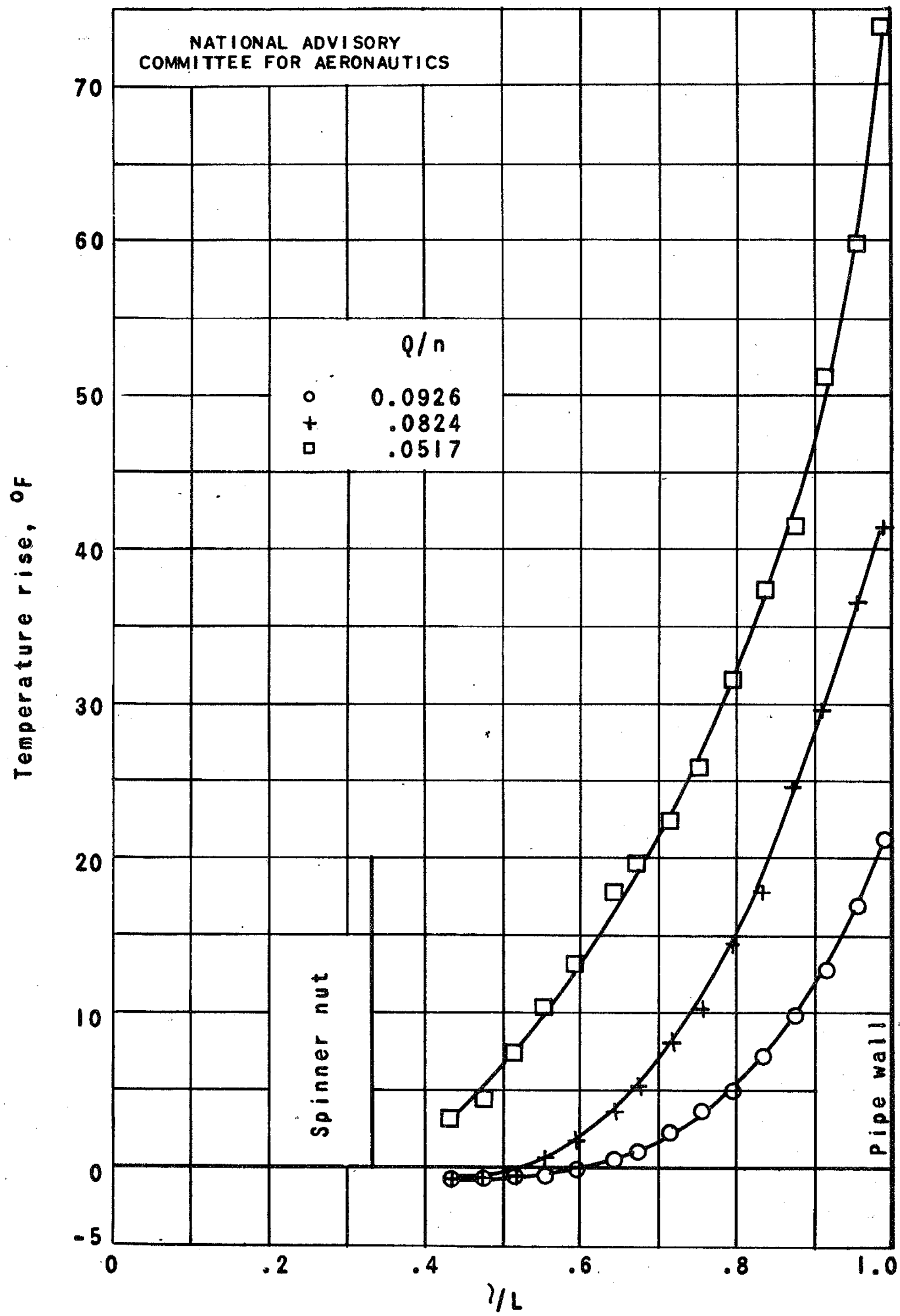
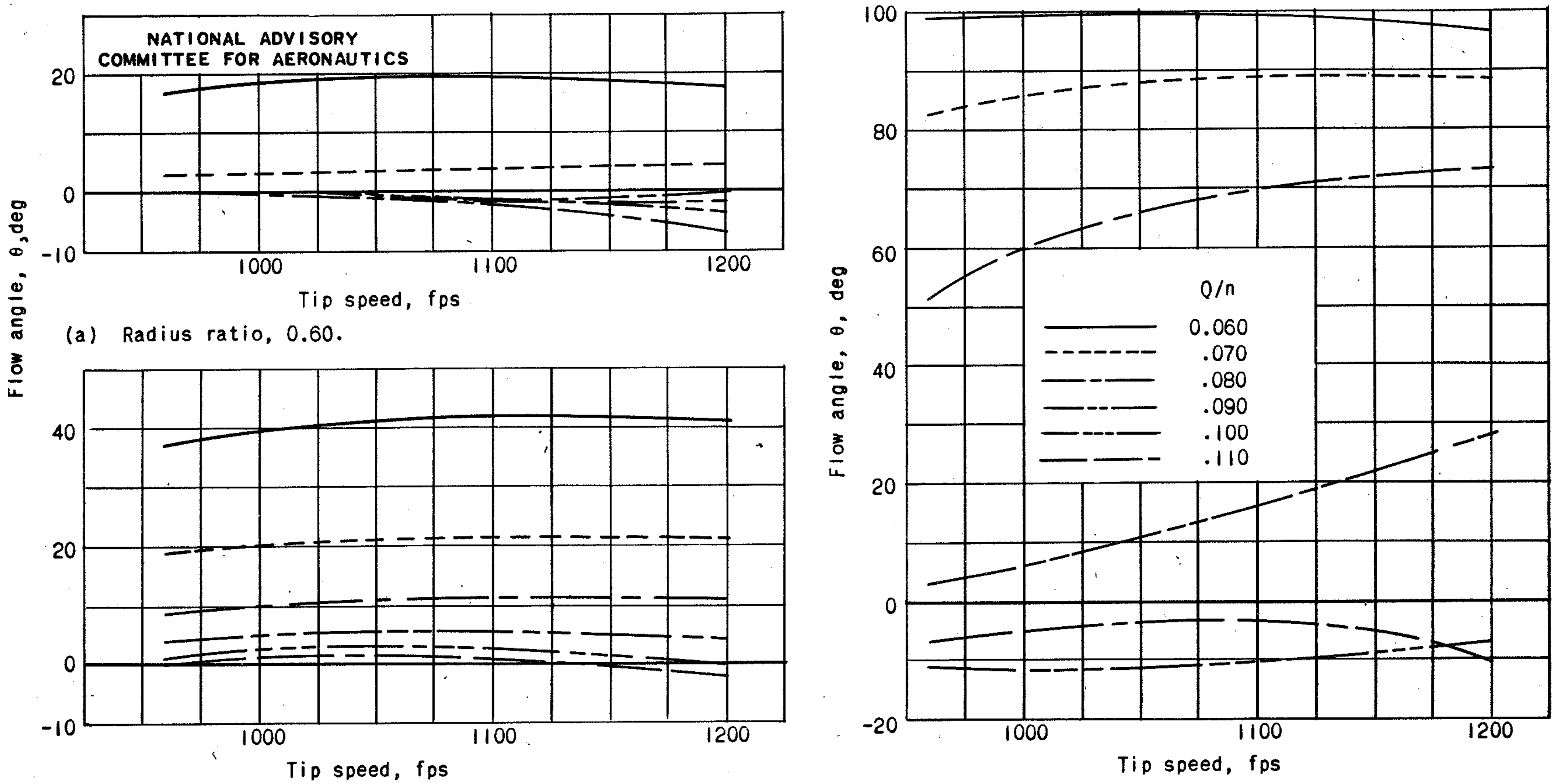



Figure 19. - The effect of various values of Q/n on the temperature gradient at the inlet of the experimental supercharger for an impeller tip speed of 1200 feet per second and an outlet pressure of 10 inches of mercury above atmospheric.

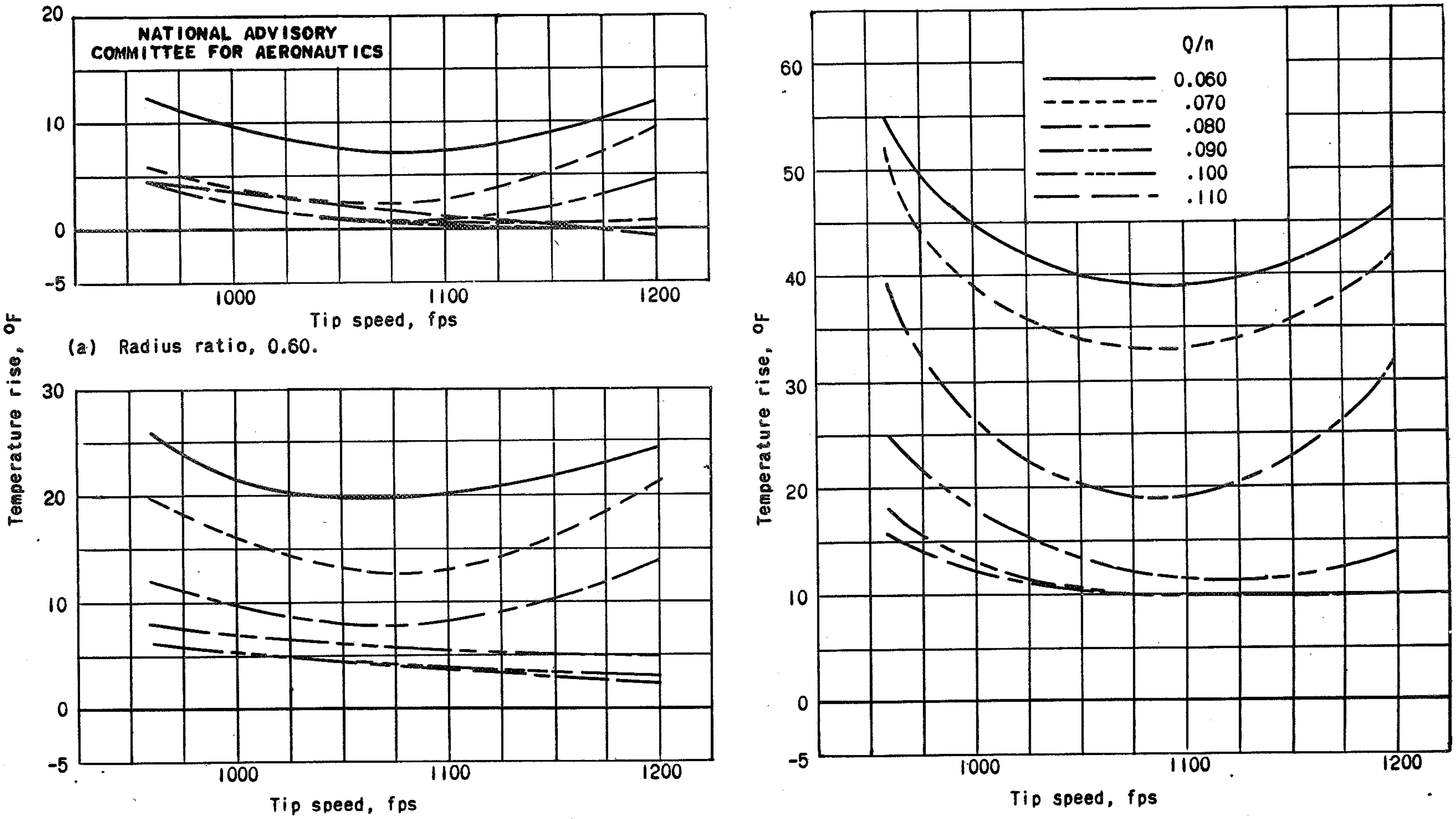



(a) Radius ratio, 0.60.

(b) Radius ratio, 0.75.

(c) Radius ratio, 0.90.

Figure 20. - Effect of impeller tip speed on the angularity of flow for various values of Q/n.




(a) Radius ratio, 0.60.

(b) Radius ratio, 0.75.

(c) Radius ratio, 0.90.

Figure 21. - Effect of impeller tip speed on the temperature gradient for various values of Q/n.